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MONTE CARLO GENERATORS FOR THE LHC*

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The status of two Monte Carlo generators, Helac-Phegas, a program for multi-jet processes and Vbfnlo, a parton level program for vector boson fusion processes at NLO QCD, is briefly presented. The aim of these tools is the simulation of events within the Standard Model at current and future high energy experiments, in particular the LHC. Some results related to the production of multi-jet final states at the LHC are also shown.

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The main aim of the Large Hadron Collider (LHC), which is expected to start in 2008, is the discovery of the last missing particle predicted by the Standard Model (SM), the Higgs boson. Almost as high on the agenda, however, is the search for signals of new physics beyond the SM. Background processes to these searches are mostly due to QCD interactions which are sometimes accompanied by electroweak vector bosons. The final states are characterized by a high number of jets and/or identified particles. Theoretical predictions in such cases require the computation of scattering amplitudes with a large number of external particles. The complexity of calculations grows with the number of external legs. For example, the numbers of Feynman diagrams which are needed for the computation of the $gg \to 8g$ and $q\bar{q} \to 8g$ amplitudes, are 10, 525, 900 and 4, 016, 775, respectively. In general the number of Feynman diagrams grows asymptotically factorially with the number of particles. Moreover, for a given jet configuration

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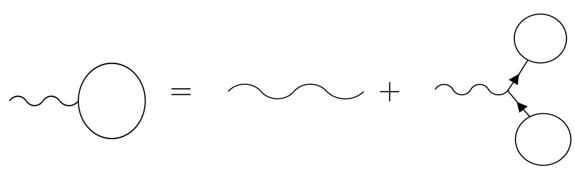
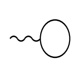
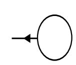
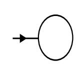
there are usually many contributing subprocesses, *e.g.* for the calculation of $pp \to e^+\nu_e + 6\,\mathrm{jets}$, 2476 subprocesses have to be taken into account. In addition, neither the color nor the spin of the partons are observed. Thus, for an amplitude with p quarks and q gluons $(2\times 3)^p(2\times 8)^q$ configurations have to be considered in principle for every phase space point. Both, the usual techniques of evaluating Feynman diagrams and straightforward summation over color and helicity configurations are in practice almost unusable. The next challenge is the phase space integration. Each amplitude peaks in a complicated way inside the momentum phase space. Direct integration is, therefore, impractical and one has to search for efficient mappings to do importance sampling in a multi-particle phase space. Clearly, new alternative techniques and automatization of calculations for multileg LHC processes is a timely task.

Over the last years new algorithms along with their implementations for computing tree-order scattering amplitudes have been proposed [1–7]. They reorganize various off-shell subamplitudes in a systematic way so that as little of the computation is repeated as possible. A scattering amplitude is computed through a set of recursive equations derived from the effective action as a function of the classical fields. These equations represent nothing else but the tree order Dyson–Schwinger (DS) equations and give recursively the n-point Green's functions in terms of the 1-, 2-, …, $(n-1)$-point functions. They hold all the information about the fields and their interactions for any number of external legs and to all orders in perturbation theory. For example in QED these equations can be written as follows:



$$b^\mu(P) = \sum_{i=1}^{n} \delta_{P=p_i} b^\mu(p_i) \sum_{P=P_1+P_2} (ig)\Pi^\mu_\nu(P_2)\gamma^\nu\psi(P_1)\varepsilon(P_1,P_2)\,, \qquad (1)$$

where

$b_\mu(P) =$  $\psi(P) =$  $\bar{\psi}(P) =$ 

describes a generic n-point Green's function with, respectively, one outgoing photon, fermion or antifermion leg carrying momentum P. $\Pi_{\mu\nu}$ stands for the boson propagator and ε takes into account the sign due to fermion antisymmetrization. In the same way recursive equations for other particles in the SM can be derived.

HELAC [7] is the only existing implementation of the algorithm based on DS equations. It is able to calculate iteratively matrix elements for an arbitrary multi-particle and multi-jet process within the SM in leptonic and hadronic collisions. For multi-jet states all elementary parton level subprocesses are taken into account. All electroweak vertices in both Feynman and unitary gauges have been included, whereas unstable particles are treated in a fully consistent way, by using either a fixed width or a complex mass scheme [8–10]. Spin and color correlations are taken into account naturally and there is no approximation involved. A substantial speed up has been obtained with Monte Carlo (MC) techniques to perform the sum over helicity and color configurations [5, 6]. The computational cost of HELAC grows like $\sim 4^n$ (3^n), which essentially counts the steps used to solve the recursive equations[1]. The program incorporates the possibility to use extended numerical precision by exploiting the virtues of FORTRAN90. The

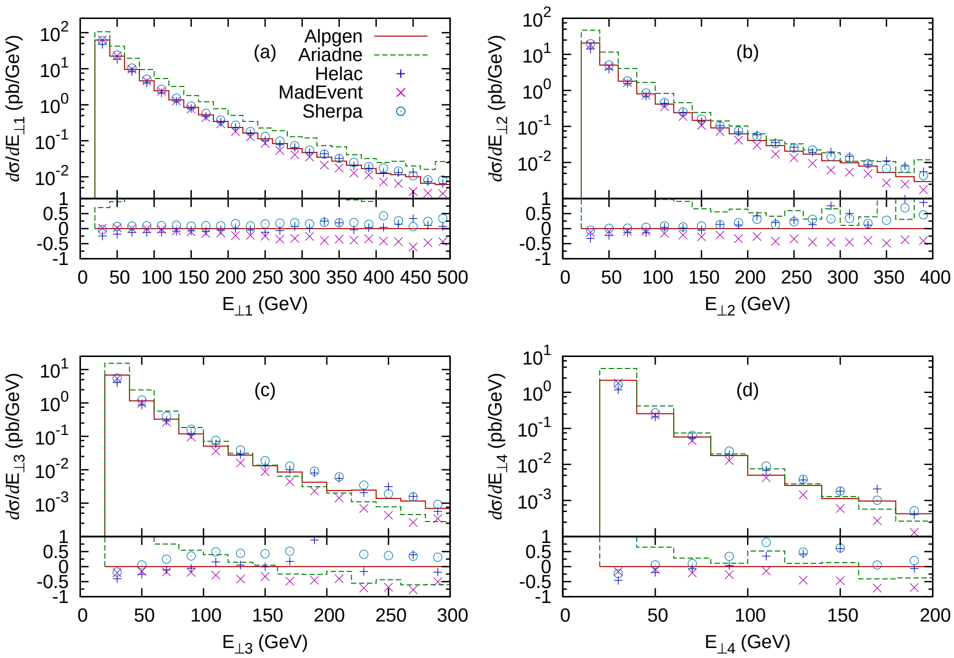


Fig. 1. Inclusive $E_\perp$ spectra of the leading 4 jets at the LHC (pb/GeV). In all cases the full line gives the ALPGEN results, the dashed line gives the ARIADNE results and the "+", "x" and "o" points give the HELAC, MADEVENT and SHERPA results, respectively.

[1] To reduce the computational complexity down to an asymptotic 3^n each 4-boson vertex must be replaced with a 3-boson vertex *e.g.* by introducing an auxiliary field represented by the antisymmetric tensor $H^{\mu\nu}$, see [5,6] for details.

user can easily switch to quadruple precision or to an even higher, user-defined precision by using the multi-precision library [11]. Finally, the peaking structure of the amplitude is dealt with by the phase space generating algorithm Phegas [12]. Phegas is the first implementation of a completely automated algorithm of multi-channel phase space mappings for an arbitrary number of external particles. It uses the information generated by Helac and automatically performs a multi-channel phase space generation, utilizing "scalarized" Feynman graphs. In the case of pp and $p\bar{p}$ collisions the cross section is also convoluted with parton distribution functions. In that case the integration is optimized by using the Parni algorithm [13]. The program makes use of the Les Houches Accord PDF Interface library (LHAPDF) [14]. It also generates a Les Houches Accord (LHA) file [15, 16] with all the necessary information needed to interface to the Pythia [17] parton shower and hadronization program. In fact, the problem of double counting of jets may arise when interfacing fixed order tree level matrix elements to parton showers. In order to deal with it, a matching algorithm has to be applied, which provides a smooth transition between the part of the phase space covered by parton showers and the one described by matrix elements. We have used the so-called MLM matching algorithm, see *e.g.* [18]. Let us note that a comparative study [19] of matching algorithms implemented in different MC codes namely Helac, Alpgen [20], Ariadne [21], MadEvent [22, 23] and Sherpa [24, 25] has recently been published for the $W + n$ jets production with kinematics corresponding to the TeVatron and the LHC. As an example in Fig. 1, inclusive $E_\perp$ spectra of the leading 4 jets at the LHC (pb/GeV) for Alpgen, Ariadne Helac, Madevent and Sherpa are given. Fig. 2 shows graphically the cross-section systematic

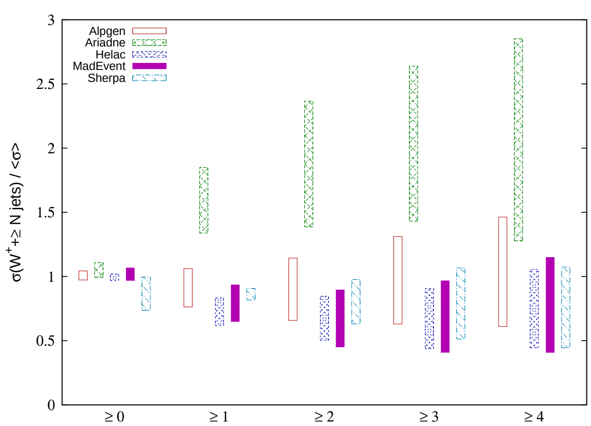


Fig. 2. Range of variation for the LHC cross-section rates of the five codes, normalized to the average value of the default settings for all codes in each multiplicity bin.

error ranges. For each multiplicity, the rates are normalized to the average of the default values of all the codes. The complete information on the simulation details can be found in Ref. [19]. The HELAC-PHEGAS package [7] is now publicly available[2], see also [26–30].

As we have seen, if one is content with the tree level calculations only, it is possible to go to high orders with up to 8–10 partons in the final state. Of course, they have to be kept well separated to avoid the phase space regions where divergencies become troublesome. Soft and collinear regions can then be covered by the parton shower. However, to resolve the large scale dependence inherent in leading order calculations it is necessary to include NLO corrections. The complexity of a calculation increases with the order in perturbation theory. Currently available NLO calculations are restricted to the 2–4 final state particles only[3]. More importantly, only one MC library, MC@NLO [32], incorporates NLO QCD matrix elements consistently into a parton shower framework. A general purpose NLO MC library does not exist yet. However, there are a few MC programs for specialized processes.

In particular, VBFNLO belongs to this category[4] when various Vector Boson Fusion (VBF) processes are concerned. For example, the $\bar{q}Q \to \bar{q}QH$ VBF process can be visualized as the elastic scattering of two quarks mediated by the t-channel W or Z exchange with the Higgs boson radiated off the weak boson propagator, see Fig. 3. It is expected to provide a copious source of Higgs bosons in pp collisions at the LHC and together with gluon fusion, it represents the most promising production process for Higgs boson discovery. Once the Higgs boson has been found and its mass determined, the measurement of its couplings to gauge bosons and fermions will

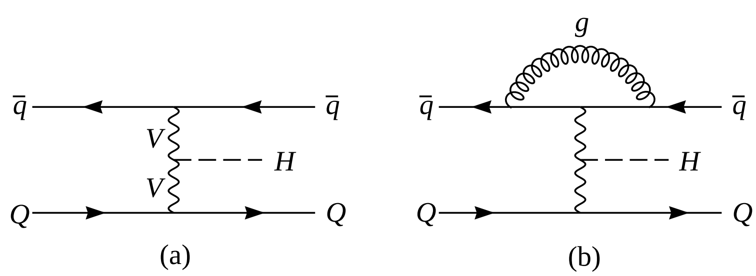


Fig. 3. Feynman graphs contributing to $\bar{q}Q \to \bar{q}QH$ at (a) tree level and (b) including virtual corrections to the upper quark line.

[2] `http://helac-phegas.web.cern.ch/helac-phegas/`

[3] There are no NLO programs for the LHC with more than 3 hard particles in the final state. NLO programs with four particles in the final state are available only for e^+e^- annihilation. See *e.g.* [31] for a recent review on this subject.

[4] `http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/`

be of main interest. Here VBF will be of the central importance since it allows for independent observation in the $H \to \gamma\gamma$, $H \to b\bar{b}$, $H \to \tau^+\tau^-$, $H \to W^+W^-$ and $H \to invisible$ channels. This multitude of channels is crucial for separating the effects of different Higgs boson couplings. VBF measurements can be performed at the LHC with statistical accuracies on cross sections times decay branching ratios, $\sigma \times B$ reaching (5–10)% [33,34]. Theoretical predictions of the SM production cross section with error well below 10% are required. This clearly entails knowledge of the NLO QCD corrections. In order to distinguish the VBF Higgs boson signal from backgrounds, stringent cuts are required on the Higgs boson decay products, as well as on the two forward quark jets which are characteristic for VBF. This can be best addressed with Vbfnlo which contains, among others, Higgs boson production in the narrow resonance approximation [35]. In addition, anomalous couplings have been added for the Higgs boson [36]. The production of $W \to l\nu_l$ and $Z \to l^+l^-$ [37] bosons in association with two jets is also included in the program since it is an important background. Moreover, W^+W^- [38] and ZZ [39] production via vector-boson fusion with subsequent leptonic decay of the Ws and Zs with all resonant and non-resonant Feynman diagrams and spin correlations of the final-state leptons have been implemented. Let us note that in all these cases any identical fermion effects, *i.e.* s-channel exchange and interference effects of t-channel and u-channel diagrams are systematically neglected. In the phase space region where VBF can be observed experimentally, with widely-separated quark jets of very large invariant mass, the neglected terms are strongly suppressed by the large momentum transfer in one or more weak-boson propagators. For the evaluation of partonic matrix elements, amplitude techniques of [40,41] have been employed. The calculation of NLO QCD corrections is based on the dipole subtraction formalism, in the version proposed by Catani and Seymour [42]. Radiative corrections to a single quark line have only been calculated, since any interference between subamplitudes with gluons attached to both the upper and the lower quark lines vanishes identically at order α_s, because of the color singlet nature of the exchanged weak boson. The virtual contributions, obtained from the interference of one-loop diagrams with the Born amplitude, include self-energy, triangle, box and pentagon corrections. A Passarino–Veltman reduction of tensor integrals [43], which is stable in the phase space regions covered by VBF-type reactions is implemented up to box-type virtual corrections. For pentagon contributions, however, this technique gives rise to numerical instabilities, if kinematical invariants, such as the Gram determinants, become small. Therefore, the reduction scheme proposed by Denner and Dittmaier for the tensor reduction of pentagon integrals [44,45] has been used. In all cases the QCD corrections are modest, changing total cross sections by less than 10%. Remaining scale uncertainties are at the few percent level. Modest corrections are also present in distributions. Let us note that VBFNLO is a fully flexible MC program. Arbitrary cuts can be implemented and independent scales can be fixed for the radiative correction on the upper and lower quark lines. Moreover, various scale choices and PDF sets are available in the later case also through the LHAPDF library. Finally, the program generates an LHA file.

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