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MadEvent: automatic event generation with MadGraph*

Fabio Maltoni and Tim Stelzer

Department of Physics, University of Illinois at Urbana-Champaign
1110 West Green Street, Urbana, IL 61801, USA
E-mail: tstelzer@uiuc.edu, maltoni@uiuc.edu

Abstract: We present a new multi-channel integration method and its implementation in the multi-purpose event generator `MadEvent`, which is based on `MadGraph`. Given a process, `MadGraph` automatically identifies all the relevant subprocesses, generates both the amplitudes and the mappings needed for an efficient integration over the phase space, and passes them to `MadEvent`. As a result, a process-specific, stand-alone code is produced that allows the user to calculate cross sections and produce unweighted events in a standard output format. Several examples are given for processes that are relevant for physics studies at present and forthcoming colliders.

Keywords: Standard Model, QCD, Hadronic Colliders.

*http://madgraph.physics.uiuc.edu

Contents

1. Introduction

The high energy and luminosity of the present and future colliders, from the Tevatron to the Large Hadron Collider to the proposed 500 GeV Linear Collider, will offer the widest range of physics opportunities for the exploration of the high-energy frontier. Among the highest priorities is understanding not only the nature of the electroweak symmetry breaking but also the mechanism through which the electroweak scale stabilizes. Simple and very robust arguments indicate that this scale should be less than one TeV, very much in the reach of the above mentioned colliders. At this energy, multijet final states in association with leptons or missing energy constitutes the most interesting data samples. The quest for the Higgs boson(s) and/or for supersymmetric particles will rely on our ability to predict and understand the standard-model processes which are the backgrounds to these searches. In general, not only pure QCD interactions lead to multijet configurations, but also the production of vector bosons or top quarks that subsequently decay into quarks yield similar signatures with many particles in the final state.

Although straightforward in principle, the evaluation of the cross sections and especially the generation of unweighted events for such processes is not a trivial task. First of all, the number of subprocesses contributing to a process can be fairly large. For instance, for $W+4$-jet production in pp collisions there are 498 distinct parton-parton subprocesses. Clearly, it is desirable to automate not only the identification of these subprocesses, but also their integration and event generation.

Unfortunately, the complexity of each subprocess also grows quickly with the number of particles in the final state. If the amplitudes involve identical particles then the growth is factorial. A typical example, amply discussed in the literature [1]–[3], is the computation of n-gluon amplitudes where already for a relatively small number of gluons produced, say $n \gtrsim 6$, clever reorganizations of the perturbative expansion have to be employed to reduce the factorial growth to a more manageable exponential one [4, 5].

The second step is the integration of the squared amplitude over the phase space, which is necessarily performed using Monte Carlo techniques. This task involves solving several issues. In the first place, the amplitude results in a very complicated function of the momenta which displays sharp peaks in many region of the phase space. In order to achieve an efficient numerical integration, one needs to identify the position of these peaks and to map them onto several different sets of variables, which are usually referred to as "channels". In principle, both tasks are not trivial. Fortunately, a standard Feynman diagram expansion provides the necessary information on the structure (position and shape) of the peaks in the matrix elements. In general, the main source of variation of the amplitude in a given region of the phase space can be associated with one (or more) of the propagators in one (or more) diagrams becoming large. Typically, this happens either when collinear-divergent limits are approached or when virtual massive particles, with a small width, are close to their mass-shell.

At present, the available codes for the automated generation of phase space are based on identifying singularities in Feynman diagrams [6, 7]. As we will show in the following, we use a similar approach for generating the phase-space mappings. However, our method differs from the previous ones in that we propose to exploit the information gathered from the Feynman diagrams to reorganize and simplify the way we perform the integration over the various channels.

In this paper we present a new multi-channel integration method, which we will call Single-Diagram-Enhanced, and its implementation in the new multi-purpose event generator `MadEvent` which is powered by a new version of `MadGraph` [8]. Given a user process, `MadGraph` automatically generates the amplitudes for all the relevant subprocesses and produces the mappings for the integration over the phase space. This process-dependent information is passed to `MadEvent`, and a stand-alone code is produced that allows the user to calculate cross sections and to obtain unweighted events. Once the events have been generated (and all the necessary information stored[1]) they may be passed to any shower Monte Carlo program (such as `HERWIG` [10] or `PYTHIA` [11, 12]) where partons are perturbatevely evolved through the emission of QCD radiation, and eventually turned into physical states (hadronization).

This paper is organized as follows. In the next section 2 we present our method for mapping the phase space and integrating the squared amplitude. In section 3, we provide some examples of the results that can be obtained with `MadEvent`. The conclusions and a brief discussion of the outlook are addressed in the last section.

2. Single-diagram-enhanced multi-channel integration

In this section we present our approach for integrating a generic squared amplitude over the phase space of the final-state particles. We first review the usual multi-channel integration method, following closely ref. [13], since this serves to establish the notation and allows us to point out the issues relevant to the subsequent discussion.

[1]In addition to the usual kinematic quantities, such as masses and momenta, the spin, the color connection, and the flavour of each of the final-state partons may be needed for each event. This information is stored in the "Les Houches" format [9].

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Let us consider $f(\vec{\Phi})$ the function to be integrated over the set of phase-space variables $\vec{\Phi}$. Given N the number of particles in the final state, $\vec{\Phi}$ is of dimension $d = 3N - 4$. In order to account for the complex structure of f several mappings of the Monte Carlo variables $\vec{x} \in [0,1]^d$ are introduced and each of them generates a different probability density, $g_i(\vec{\Phi})$, $i = 1, \ldots, n$, where n is the total number of channels.[2] The optimization of the relative importance of the different channels is achieved by introducing a set of weights $\alpha_i, \sum_{i=1}^n \alpha_i = 1, \alpha_i \geq 0$, and defining a total probability density $g(\vec{\Phi}) = \sum_{i=1}^n \alpha_i g_i(\vec{\Phi})$, which combines the weights of each channel and is still correctly normalized. The weight of a phase space point $\vec{\Phi}$ can be written as $w(\vec{\Phi}) = f(\vec{\Phi})/g(\vec{\Phi})$ and the result of the Monte Carlo integration and its variance are:

$$\begin{aligned} I &= \int d\vec{\Phi}\, g(\vec{\Phi})\, w(\vec{\Phi}) = \int d\vec{\Phi} f(\vec{\Phi})\,, \\ V(\alpha) &= \int d\vec{\Phi}\, g(\vec{\Phi})\, w(\vec{\Phi})^2 = \int d\vec{\Phi} \frac{f(\vec{\Phi})^2}{g(\vec{\Phi})}\,. \end{aligned} \tag{2.1}$$

As made explicit in the notation, the result of the integration does not depend on the choice of the α_i (which can even differ iteration by iteration), while the variance does. The aim of the multi-channel approach is to find the best set of α_i which minimizes the variance V. Several strategies can be followed [13]. Here, we just comment on a few important aspects of this approach.

In the first place we note that for each point in the phase space, independently from the actual channel chosen, the determination of $g(\vec{\Phi})$ implies the computation of the contributions from all channels. As long as the number of channels is not very large and/or the computational burden for calculating $g(\vec{\Phi})$ is much smaller than that for $f(\vec{\Phi})$, this might not be a serious problem. However, in general, this procedure is inefficient. During the integration, the relative weight of each channel changes due to the optimization of the α_i. In particular, even if some of the channels become less and less important compared to others, the time spent to calculate their contributions remains the same. Another point of weakness is that, even if the evolution of each of the α_i can be chosen to be independent from the others, in practice the α_i are correlated. Predicting the behavior and/or the stability of an integration with a large number of channels is very difficult and jeopardizes the robustness of the solution.[3]

We argue that there is a natural way to overcome the above limitations and to calculate the integral of a squared amplitude over the phase space in an efficient way. The idea is very simple and is based on the following observation. Assume that the function to be integrated could be written in terms of a basis of n functions f_i such that:

$$f = \sum_{i=1}^{n} f_i \qquad \text{with} \qquad f_i \geq 0\,, \qquad \forall\, i\,, \tag{2.2}$$

[2]Each probability density $g_i(\vec{\Phi})$ is related to the mapping through $\vec{\Phi} = G_i^{-1}(\vec{x})$, where $G_i(\vec{\Phi})$ is the primitive of $g_i(\vec{\Phi})$.

[3]This aspect can in practice hamper the possibility of using many channels if the mapping g_i are obtained by a stratified Monte Carlo method.

and such that the peak structure of each f_i can be efficiently mapped by a single channel g_i. Then, the integration of f reduces to:

$$I = \int d\vec{\Phi} f(\vec{\Phi}) = \sum_{i=1}^{n} \int d\vec{\Phi}\, g_i(\vec{\Phi})\, \frac{f_i(\vec{\Phi})}{g_i(\vec{\Phi})} = \sum_{i=1}^{n} I_i\,, \tag{2.3}$$

i.e., to a sum of n independent integrations. In so doing a single channel g_i is associated to each integration I_i and no set of weights α_i (and related functions $g(\vec{\Phi})$ and $w(\vec{\Phi})$) need to be introduced. For a generic integration problem, the identification of such a basis might be too difficult and the above method be simply not viable. However, in the case at hand, a natural decomposition arises from the physical content of the process. We propose to use the following basis:

$$f_i = \frac{|A_i|^2}{\sum_i |A_i|^2} |A_{\rm tot}|^2\,, \tag{2.4}$$

where A_i is the amplitude corresponding to a single Feynman diagram and $A_{\rm tot} = \sum_i A_i$ is the total amplitude. It is clear that each f_i in eq. (2.4) satisfies the conditions (2.2) and form a "complete" basis.[4] More importantly, the peak structure of each f_i is the same as of the single squared amplitude $|A_i|^2$. Finding the suitable mapping g_i is therefore straightforward, since it can be derived from the propagator structure of the corresponding Feynman diagram. We will refer to the above algorithm as Single-Diagram-Enhanced multi-channel integration.

Decomposing the integration of the amplitude into n independent integrations has immediate advantages. First, in contrast to the standard multi-channel integration, the evaluation of the weight in one channel does not require the computation of the others. This entails that, from the statistics point of view, in the Single-Diagram-Enhanced integration method the complexity of the computation does not increase with the number of channels.

Second, the Single-Diagram-Enhanced integration is parallel in nature. Integrations in each channel can be performed by using different resources and the results combined only at the very end. Considering the latest developments in this field, such as the availability of PC farms at low cost, we reckon this as an alluring property of this approach.

A third useful aspect of our method is that, given a target accuracy of the integration, it is trivial to reweight the channels so that those whose contributions to the total result is small (large) are evaluated with a smaller (greater) number of Monte Carlo points. For instance, in our implementation, first we perfom a run with a minimum fixed number of points for each channel to obtain an estimate of the I_i (and therefore also of the total integral I). Then, when necessary, we improve the accuracy of a single integration based on how large is its contribution to the final result, using the ratio I_i/I as an indicator. This realizes in practice the desirable property that the computational time spent on a single channel should be proportional to its relevance to the final result.

[4]Eq. (2.4) is analogous to the procedure suggested by Odagiri [14] to extract the leading color behaviour of QCD amplitudes.

colliders	Tevatron: $p\bar{p}$ @ 2 TeV LHC: pp @ 14 TeV
QCD and EW couplings and parameters	$\alpha_S(M_Z) = 0.1185$ $\alpha_{\rm em}(M_Z) = 1/128.9$, $\sin^2\theta_W = 0.2312$ CKM matrix: diagonal
p.d.f.	CTEQ5L (parametric)
scales	$\mu_F = \mu_R = M_Z$
vector boson masses and widths	$m_Z = 91.188\,\mathrm{GeV}$, $\Gamma_Z = 2.495\,\mathrm{GeV}$ $m_W = 79.96\,\mathrm{GeV}$, $\Gamma_W = 2.06\,\mathrm{GeV}$
heavy-quark (pole) masses	$m_t = 174.3\,\mathrm{GeV}$, $m_b = 4.7\,\mathrm{GeV}$
Higgs parameters and couplings[6]	$M_H = 120\,\mathrm{GeV}$, $\Gamma_H = 3.7\cdot 10^{-3}\,\mathrm{GeV}$ $y_t = 0.97$, $y_b = 0.017$
kinematic cuts	$E^T > 10\,\mathrm{GeV}$, $\lvert y\rvert < 2.5$, $\Delta R > 0.4$, for all the final-state particles

Table 1: Couplings and conventions used in the calculation of the benchmark cross sections.

Another interesting property of the decomposition (2.4) is its intrinsic modularity. The number of the diagrams to be included in the decomposition is completely arbitrary and dictated only by convenience. In general, the number of channels will be less than the number of Feynman diagrams. The first important example is when k identical particles are present in the final state and n can be easily reduced by a factor $k!$. Another case is when some diagrams do not display any peaked behavior and are dropped from eq. (2.4). Alternately, some diagrams can be efficiently grouped together if the form of the resulting g_i is predicted by general arguments, such as radiation coherence.

3. MadEvent at work: some examples

In this section, we present some results for processes relevant at hadron colliders, which have been obtained with `MadEvent`. The purpose is to show the versatility and the potential of our approach and also to provide benchmark cross sections for the user. Detailed information on how to use the `MadGraph/MadEvent` package together with a web interface for generating the code for a given process is available at `http://madgraph.physics.uiuc.edu`. In order to facilitate the comparison with other available codes we have chosen a very simple set of cuts and conventions, which are summarized in table 1. In particular, the cuts in transverse energy and ΔR are left quite loose so that regions of the phase space where the matrix elements peak are not left out and the efficiency of our integration technique can be fully tested.[5]

In table 2 we present the cross sections involving the production one or more vector bosons in association with jets, both at the Tevatron and LHC. Apart from the interest they

[5] In fact, at the LHC such cuts are not sufficient to ensure a good behaviour of the perturbative series for some of the cross sections shown, as it is apparent by comparing the processes with n jets with the corresponding ones with $(n+1)$ jets.

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Process+n jets	n	order	unit	Tevatron	LHC
	0			758	3850 (3450)
	1			182	1700 (1520)
$e^+\nu_e\,(e^-\bar{\nu}_e)$	2	$\alpha_{\rm em}^2\alpha_S^n$	pb	46.6	742 (642)
	3			12.0	337 (279)
	4			3.19	156 (122)
	0			210	1000
	1			46.2	398
e^+e^-	2	$\alpha_{\rm em}^2\alpha_S^n$	pb	12.6	179
	3			3.30	79.0
	4			0.871	35.1
	0			427	2330 (1770)
$e^+\nu_e\,(e^-\bar{\nu}_e)\;b\bar{b}$	1	$\alpha_{\rm em}^2\alpha_S^{n+2}$	fb	195	2950 (2330)
	2			73.1	2600 (1980)
	0			165	3880
$e^+e^-b\bar{b}$	1	$\alpha_{\rm em}^2\alpha_S^{n+2}$	fb	79.3	3080
	2			28.0	1770
	0			9.28	46.3
W^+W^-	1	$\alpha_{\rm em}^2\alpha_S^n$	pb	3.84	37.0
	2			1.23	25.3
	0			1.49	10.0 (7.25)
$W^+(W^-)Z$	1	$\alpha_{\rm em}^2\alpha_S^n$	pb	0.633	10.7 (7.31)
	2			0.209	9.15 (6.40)
	0			1.04	6.70
ZZ	1	$\alpha_{\rm em}^2\alpha_S^n$	pb	0.440	4.95
	2			0.133	2.97

Table 2: Benchmark cross sections for single and double vector boson production in association with jets at hadron colliders. The decays into leptons, $W \to e\nu_e$ and $\gamma^*/Z \to e^+e^-$, are included in the single vector boson cross sections and cuts, as described in the text, are applied to all the final state particles (jets and leptons). In the case of WW, WZ, ZZ production, the vector bosons are not decayed and are produced on shell. Statistical errors for all processes are at the percent level.

might have on their own, these processes contribute to some of the most important backgrounds for top-quark studies (W+jets, $Wb\bar{b}$+jets), for the Higgs searches (W^+W^-+jets, $Wb\bar{b}$+jets, ZZ+jets) and for SUSY particles searches (Z+jets, with $Z \to \nu\bar{\nu}$). In the single vector boson production, final states are leptons and so that the vector bosons are not contrained to be on-shell. This entails, for instance, that cross sections involving a Z boson, correctly include the diagrams where $\gamma^* \to \ell^+\ell^-$ and their interference with $Z^* \to \ell^+\ell^-$.

For simplicity, in the case of double vector boson production, we present the results where the vector bosons are produced on shell and are not decayed. Nonetheless, we stress that `MadEvent` correctly handles also the decays, where non-trivial phase-space mappings have to be introduced. An example is provided by W^+W^- production where contributions

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Process+n jets	n	order	unit	Tevatron	LHC
$t\bar{t}$	0	α_S^{n+2}	pb	7.67	579
	1			3.53	762
	2			1.24	660
	3			0.385	460
$b\bar{b}$	0	α_S^{n+2}	nb	832	15000
	1			115	3010
	2			29.0	1110
	3			6.35	356
$t\bar{t}b\bar{b}$	0	α_S^{n+4}	fb	14.5	3890
	1			8.21	6440
	0	$\alpha_{\rm em}^2\alpha_S^{n+2}$	fb	1.14	336
	1			0.747	380
$b\bar{b}b\bar{b}$	0	α_S^{n+4}	pb	86.1	4050
	1			41.0	546
	0	$\alpha_{\rm em}^2\alpha_S^{n+2}$	fb	676	16100
	1			428	4090

Table 3: Benchmark cross sections for heavy-quark pair production in association with jets (light quarks and gluons) at hadron colliders. The heavy quarks are produced on shell and are not decayed. In $t\bar{t}b\bar{b}$ and $b\bar{b}b\bar{b}$ production, contributions from the exchange of a virtual Higgs have been excluded. Cuts, as described in the text, are applied to all the final state particles. Statistical errors for all processes are at the percent level.

from diagrams where $\gamma^*/Z \to W^+W^- \to \ell^+\ell^-\nu\bar{\nu}$ appear, which demand particular care. In this case, there are different regions in the phase space which can give large contributions, coming from the Z and one of the W's, or both W's being on shell. We have ensured that the procedure used for the mapping of the phase space automatically accounts for all the possibilities, so that no approximation is introduced.

When possible, we have compared our results with the ones obtained by running available codes (such as `VECBOS` [15], `Wbbgen` [16] and `MCFM` [17]) and found agreement at the percent level. We plan to conduct a detailed set of comparisons with the recently released `Alpgen` [18] in the future.

Table 3 contains the cross sections for the production one or more heavy-quark pairs in association with jets, both at the Tevatron and LHC. In the case of $t\bar{t}b\bar{b}$ production we also give the cross sections at order $\alpha_{\rm em}^2\alpha_S^2$. These last ones constitute the irreducible backgrounds in the search of the Higgs when it is produced in association with a top-quark pair. Also, the cross section for two bottom-quark pairs in association with jets are listed. In the case of two bottom-quark pairs we have also performed a detailed comparison with the results of ref. [19] and found agreement at the percent level.

In table 4 cross sections are given for the production of an Higgs boson in association with a top-quark pair, with jets (“W-boson fusion”) and in association with a W boson, both at the Tevatron and LHC.

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Process+n jets	n	order	unit	Tevatron	LHC
h	2	$\alpha_{\rm em}^3\alpha_S^{n-2}$	fb	157	1550
	3			89.3	1000
$t\bar{t}h$	0	$y_t^2\alpha_S^{n+2}$	fb	7.30	545
	1			3.14	830
	2			1.00	852
$W^+(W^-)h$	0	$\alpha_{\rm em}^2\alpha_S^n$	fb	67.9	563 (391)
	1			29.3	425 (290)
	2			9.11	250 (168)
	3			2.34	137 (89)

Table 4: Benchmark cross sections for Higgs production in association with a top-quark pair, with jets (EW processes) and in association with a W boson, at hadron colliders. The heavy quarks and the Higgs and the W are produced on shell and are not decayed. Cuts, as described in the text, are applied to all the final state particles. Statistical errors for all processes are at the percent level.

Before closing this section, we stress that although the results in this paper have been presented in terms of total cross sections, MadEvent is mainly an event generator. The user can input the desired integrated luminosity or the total number of unweighted events as desired. For instance, for each of the processes considered here, ten thousands unweighted events were generated and stored in the Les Houches format [9].[7] The efficiency of the unweighting procedure depends on the specific process, cuts and how much time is spent adapting the grids.

$W+n$ jets	I	II	III	Tot
1	6.0	3.0	0.5	1.9
2	6.0	4.0	0.5	8.1
3	6.0	5.0	0.6	6.9
4	6.0	6.0	0.7	9.6

Table 5: Generated events, in units of 10^6, for each of the three steps of the integration procedure for $W+n$ jets production. The total number of events necessary for generating a set of ten thousands unweighted events is shown in the fourth column.

To illustrate the efficiency of our procedure we have collected in table 5 the number of events used to generate ten thousands unweighted events for $W+n$ jets production, with $n=1,\ldots,4$. Our implementation consists of three steps. In the first one a "survey" of the phase space is performed to gather information on the relative importance of each channel. During this step the grids of the adaptative Monte Carlo are kept fixed. In the second phase the integrations on the most important channels are "refined" by letting the Monte Carlo adjust the grids. In the third and final phase, events are generated, keeping the grids fixed, to accumulate the statistics necessary to collect the desired number of unweighted events. The above procedure, with the exact same implementation, has been used to obtain all the results presented in this paper. Although it could be improved in some specific case, it has shown to work in general, to be robust and, most importantly, to produce the desired results without any intervention from the user. To have an idea of the overall performance of our approach, consider the production of $W+3$ jets. There are 53 parton subprocesses,

[7] The interested reader can find them at the MadEvent web page.

with up to 54 Feynman diagrams contributing to each of them. On a 2 GHz Linux PC, the integration over the phase space, including the generation of ten thousands unweighted events, takes about two hours.

4. Conclusions and outlook

In this paper we have introduced a new integration method, called Single-Diagram-Enhanced multi-channel integration, and its implementation in the multi-purpose event generator `MadEvent`.

We have discussed how the problem of integrating over the phase space amplitudes that involve a rather large number of particles in the final state can be reduced to the integration of amplitudes associated to single Feynman diagrams. The latter are much simpler tasks and can be tackled by many of the techniques already present in the literature. Our method best applies to the automated computation of cross sections (and, more importantly, to the generation of unweighted events) for processes where many different parton subprocess contribute, such as vector boson production in association with jets at hadron colliders and many others.

We have presented some applications of `MadEvent`, a multi-purpose event generator based on the above ideas, to studies relevant at the present and forthcoming colliders. All the necessary steps to generate a set of unweighted events are performed automatically. The user only inputs the process and the desired integrated luminosity or the total number of unweighted events.

Although in principle there is no limitation to the number of particles that can be considered in the final state, in practice this still depends on the complexity of the process itself and on the total number of Feynman diagrams involved. Currently, the package is limited to ten thousands diagrams per subprocess. So, for example, W+5 jets is feasible but close to the present limit.

Several improvements that will extend the ability of `MadGraph` to deal with a larger number of QCD partons are under study. One necessary step is the "factorization" of the amplitude in order to reduce the complexity of the calculation from a factorial growth to an exponential one, as already achieved for non-QCD amplitudes in refs. [20]–[22] and extended to the QCD amplitudes in refs. [4, 20, 18]. In the latter case, a reorganization of the color structure is also needed and the sum over the colors of the external QCD partons can be efficiently performed by a Monte Carlo integration. Work in this direction is in progress [23].

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[7] In fact Γ_H and y_b do not enter the results presented here, but we prefer to leave them as a reference for the user.

References

[1] F.A. Berends and W.T. Giele, *Recursive calculations for processes with N gluons*, *Nucl. Phys.* **B 306** (1988) 759.

[2] F.A. Berends, W.T. Giele and H. Kuijf, *On six jet production at hadron colliders*, *Phys. Lett.* **B 232** (1989) 266.

[3] M.L. Mangano and S.J. Parke, *Multiparton amplitudes in gauge theories*, *Phys. Rept.* **200** (1991) 301.

[4] P. Draggiotis, R.H.P. Kleiss and C.G. Papadopoulos, *On the computation of multigluon amplitudes*, *Phys. Lett.* **B 439** (1998) 157 [hep-ph/9807207].

[5] F. Caravaglios, M.L. Mangano, M. Moretti and R. Pittau, *A new approach to multi-jet calculations in hadron collisions*, *Nucl. Phys.* **B 539** (1999) 215 [hep-ph/9807570].

[6] C.G. Papadopoulos, *Phegas: a phase space generator for automatic cross-section computation*, *Comput. Phys. Commun.* **137** (2001) 247 [hep-ph/0007335].

[7] F. Krauss, R. Kuhn and G. Soff, *Amegic++ 1.0: a matrix element generator in c++*, *J. High Energy Phys.* **02** (2002) 044 [hep-ph/0109036].

[8] T. Stelzer and W.F. Long, *Automatic generation of tree level helicity amplitudes*, *Comput. Phys. Commun.* **81** (1994) 357 [hep-ph/9401258].

[9] E. Boos et al., *Generic user process interface for event generators*, hep-ph/0109068.

[10] G. Marchesini and B.R. Webber, *Monte carlo simulation of general hard processes with coherent QCD radiation*, *Nucl. Phys.* **B 310** (1988) 461.

[11] H.-U. Bengtsson and T. Sjostrand, *The Lund Monte Carlo for hadronic processes: Pythia version 4.8*, *Comput. Phys. Commun.* **46** (1987) 43.

[12] T. Sjostrand, *High-energy physics event generation with Pythia 5.7 and jetset 7.4*, *Comput. Phys. Commun.* **82** (1994) 74.

[13] R. Kleiss and R. Pittau, *Weight optimization in multichannel Monte Carlo*, *Comput. Phys. Commun.* **83** (1994) 141 [hep-ph/9405257].

[14] K. Odagiri, *Color connection structure of (supersymmetric) QCD ($2 \to 2$) processes*, *J. High Energy Phys.* **10** (1998) 006 [hep-ph/9806531].

[15] F.A. Berends, H. Kuijf, B. Tausk and W.T. Giele, *On the production of a W and jets at hadron colliders*, *Nucl. Phys.* **B 357** (1991) 32.

[16] M.L. Mangano, M. Moretti and R. Pittau, *Multijet matrix elements and shower evolution in hadronic collisions: $Wb\bar{b} + n$ jets as a case study*, *Nucl. Phys.* **B 632** (2002) 343 [hep-ph/0108069].

[17] J. Campbell and R.K. Ellis, *Next-to-leading order corrections to $W + 2$jet and $Z + 2$jet production at hadron colliders*, *Phys. Rev.* **D 65** (2002) 113007 [hep-ph/0202176].

[18] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A.D. Polosa, *Alpgen, a generator for hard multiparton processes in hadronic collisions*, hep-ph/0206293.

[19] S. Tsuno et al., *GR@PPA_4b: a four bottom quark production event generator for $pp/p\bar{p}$ collisions*, *Comput. Phys. Commun.* **151** (2003) 216 [hep-ph/0204222].

[20] F. Caravaglios and M. Moretti, *An algorithm to compute Born scattering amplitudes without Feynman graphs*, *Phys. Lett.* **B 358** (1995) 332 [hep-ph/9507237].

[21] T. Ohl, *O'mega: an optimizing matrix element generator*, hep-ph/0011243.

[22] A. Kanaki and C.G. Papadopoulos, *Helac: a package to compute electroweak helicity amplitudes*, *Comput. Phys. Commun.* **132** (2000) 306 [hep-ph/0002082].

[23] F. Maltoni, K. Paul, T. Stelzer and S. Willenbrock, *Color-flow decomposition of QCD amplitudes*, *Phys. Rev.* **D 67** (2003) 014026 [hep-ph/0209271].

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