

New Developments in MadGraph/MadEvent

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Abstract. We here present some recent developments of MadGraph/MadEvent since the latest published version, 4.0. These developments include: Jet matching with Pythia parton showers for both Standard Model and Beyond the Standard Model processes, decay chain functionality, decay width calculation and decay simulation, process generation for the Grid, a package for calculation of quarkonium amplitudes, calculation of Matrix Element weights for experimental events, automatic dipole subtraction for next-to-leading order calculations, and an interface to FeynRules, a package for automatic calculation of Feynman rules and model files from the Lagrangian of any New Physics model.

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INTRODUCTION

With the imminent start of full-scale operation of the LHC experiment, it has become increasingly important to have efficient and versatile simulation tools, for New Physics signals as well as Standard Model backgrounds. Much effort has gone into the development of new tools in recent years, resulting in a number of packages addressing different issues. These include a new generation of general-purpose tools (Sherpa[1], Pythia8[2], Herwig++[3]), automatized matrix element generators and event generators (AlpGen[4], CompHEP[5]/CalcHEP[6], Helac[7], Whizard[8], MadGraph/MadEvent[9]), and next-to-leading order event generators (MCFM[10], MC@NLO[11]).

MadGraph/MadEvent [9] is a fully automatized tool for generation of cross sections and unweighted events for processes, both in the Standard Model and for models of New Physics. MadGraph [12] takes as input a process, specified in a simple syntax, and a model definition. It is also possible to specify multi-particle labels, the maximum order in the different couplings (e.g. QCD and QED), and require or exclude intermediate s -channel particles. MadGraph then produces all Feynman diagrams for this process and all subprocesses, as well as its matrix element expression in the form of a Fortran subroutine with calls to the helicity amplitude library HELAS [13]. MadEvent [14] is used to perform the phase space integration of the process (including any specified cuts) and produces weighted and unweighted events, using a technique dubbed “Single-diagram-enhanced multichannel integration”, which gives high unweighting efficiencies also for multi-particle final states. This technique has the addi-

tional advantage that it is trivially parallelizable to run on multi-processor clusters. Events are output to a text file following the Les Houches Accord for event generation [15], and interfaces to Pythia [16], Herwig [17] and PGS [18] allows for parton showering, hadronization and fast detector simulation.

Event generation with MadGraph/MadEvent can be done online over the Internet, on any of several dedicated computer clusters around the world, using a simple but powerful web interface. It is also possible to download the source code to compile and run locally. Complete event simulation using Pythia and PGS can be done online, directly or in stages.

RECENT DEVELOPMENTS

In version 4.0 of MadGraph/MadEvent [9], the structure of MadGraph/MadEvent was modified to allow for implementation of further models than the Standard Model, and new models were implemented, including several simple extensions of the Standard Model as well as the completely general Two Higgs Doublet Model [19] and the MSSM [20, 21]. Also a simple semi-automatized framework for addition of user-defined extensions of the Standard Model was provided. Automatization of the inclusion of new models in MG/ME has now been further extended with the introduction of the interface to the FeynRules package [22], see below.

Developments since version 4.0 include:

- Jet matching/merging between MG/ME and Pythia parton showers for Standard Model [23] and Beyond the Standard Model processes [24, 25]

- Decay chain functionality, which generates only the diagrams consistent with a specified decay chain [26]
- Particle decay width calculation and decay simulation directly in MG/ME [27]
- Creation of MadEvent process packages suitable for event generation on the Grid [28]
- A repository of LHC events and Grid packages for important Standard Model backgrounds to New Physics [29]
- MadOnium, calculation of quarkonium amplitudes in NRQCD [30]
- MadWeight, a package for calculation of Matrix Element weights of experimental events [31]
- MadDipole, automatic dipole subtraction for next-to-leading order real correction calculations [32]
- Interface to FeynRules, a Mathematica package for automatic calculation of Feynman rules and creation of event generator files directly from the Lagrangian of any New Physics model [33]

In the following we will discuss some of these developments in greater detail.

Jet matching

The simulation of jet production from QCD bremsstrahlung emissions has traditionally been done using Parton Shower (PS) Monte Carlo programs such as Pythia and Herwig, which describe parton radiation as successive parton emissions using the soft and collinear limit. This description is formally correct only in the limit of soft and collinear emissions, but has been shown to give a good description of much data also relatively far away from this limit. However, for the production of hard and widely separated jets in connection with heavy particle production, this description breaks down due to the lack of subleading terms and interference. For that case, it is necessary to use the full tree-level amplitudes for the heavy particle production plus additional partons. This description, however, diverges as partons become soft or collinear. In order to describe both these areas in phase space, the two descriptions must be combined, without double counting or gaps between different multiplicities. An additional physical requirement is that such a procedure gives smooth distributions, and interpolates between the parton shower description in the soft and collinear limits and the matrix element description in the limit of hard and widely separated partons. Several procedures have been proposed, including the CKKW [34, 35], Lönnblad [36] and Mangano [37] schemes. These different procedures are

in substantial agreement and give consistent results at hadron colliders [23, 38].

Two matching schemes are implemented in MadGraph/MadEvent interfaced to Pythia. The first is a version of the Mangano scheme, but using k_T jets instead of cone jets in the jet matching step. The details of this scheme is described in sec. 2.4 of [23]. This scheme now works with both the “old” (virtuality-ordered) and the “new” (p_T -ordered) Pythia parton showers. The second is a new scheme, which uses the feature of the p_T -ordered parton showers of Pythia 6.4 that it stores the k_T of the first emission in the parton shower in a common block. An event is generated by MadEvent, with QCD emission α_s values calculated as done in the parton shower, using the k_T values of the event clustered with the k_T algorithm (as described in [23]). The event is passed to Pythia and showered using the p_T -ordered shower, which reports the k_T value of the first emission Q_{\max}^{PS} . This value is then compared to the matching scale Q_{match} , and the event is discarded if $Q_{\max}^{\text{PS}} > Q_{\text{match}}$. The exception is for the highest parton multiplicity sample, where the event is discarded only if Q_{\max}^{PS} is higher than the lowest k_T value in the matrix element multiparton event. This matching scheme, although simple, effectively mimics the workings of the k_T -jet Mangano scheme. However, it more directly samples the Sudakov form factor used in the shower. Furthermore, the treatment of the highest multiplicity sample more closely mimics that used in the CKKW matching scheme.

Both these schemes can be used in the Standard Model as well as in processes involving New Physics. Jet matching in Beyond the Standard Model processes was recently used in a studies of model-independent gluino production at the Tevatron [39, 40], where it was noted that inclusion of Matrix Element corrections is crucial in the case of production of relatively light gluinos which decay to a near-degenerate LSP, and hence producing only soft jets. In this case, the only way to generate large missing transverse energy is when the whole gluino pair center-of-mass system is boosted in the transverse direction due to hard initial-state radiation, which is well described only using jet matching.

Further studies of the effects of matching of jets in gluino and squark production are underway, see [24, 25].

Decay chains

For precision studies of production and decay of new particles, many features can be important. In particular, different types of New Physics can often be distinguished using kinematical differences in decay chains due to differences of spins of the intermediate particles. For example, studies have shown that invariant masses between

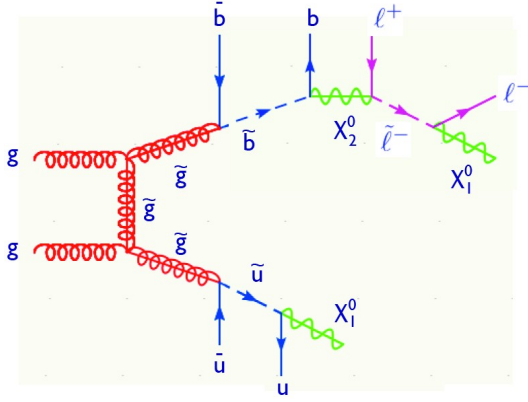


FIGURE 1. An example of a decay chain that can be generated using the decay chain functionality of MadGraph/MadEvent.

lepton pairs [41] and leptons and b jets [42] can be used to differentiate between Supersymmetry and Universal Extra Dimensions. However, in order to correctly capture these differences in simulations, it is necessary that the simulations keep the full spin correlations in the decays. Also other effects can be important, such as finite-width effects and interference effects from non-resonant diagrams [43].

Since MadGraph/MadEvent uses the full set of Feynman diagrams for any process, it automatically keeps all spin correlations, as well as finite-width effects and interference effects. However, running MadGraph for many final state particles has been forbiddingly slow, due to the large number of diagrams and diagram topologies. This situation has now been considerably improved through the introduction of the new decay chain functionality, which radically reduces diagram generation times for decay chain-type processes, and allows for up to 10 external particles in a process. An example of such a process is shown in Fig. 1. This process can be specified using the following syntax:

$$gg > (go > u (u1 > un1))(go > b (b1 > (b(n2 > mu + (mu1- > mu - n1))))))$$

(without line break.) Only diagrams conforming to this decay chain specification are generated. In the subsequent MadEvent event generation, all specified intermediate resonances are forced to be onshell (i.e., have a virtuality at most a given number of widths off their pole mass).

This technique for simulating decay chains has a number of advantages over conventional simulation methods:

- The full matrix element is used, automatically keeping all spin correlations in production and decay
- Particle widths are correctly taken into account

- $1 \rightarrow N$ decays are possible while still keeping all correlations
- Non-resonant contributions can be included only where they are relevant

It might be worthwhile to note that although this generation is considerably faster than generation of the full multi-final state matrix element including all interfering diagrams, it is still slower than the conventional generation of the central process with consecutive decays done in a second step. For scalar particle production in particular, where no spin correlations are needed, it is more efficient to use the MadGraph decay chain formalism up to the production of the scalar particles, and then perform the decay of the scalar particles using some decay tool such as BRIDGE [44] or the MadGraph/MadEvent decay width functionality, described below.

As a complement to the decay chain formalism described above, we have also implemented the calculation of partial decay widths and simulation of decay for unstable particles. This is done by specifying the process according to the syntax

$$A > BCD\dots$$

which indicates the decay of particle A to particles $BCD\dots$. Multiparticle labels can be used as usual for the decay products. When now MadEvent is run, it will present the partial decay width instead of the cross section, and generate events corresponding to the decay of A in its rest frame. These decays can subsequently be boosted and combined with an event file describing production of A particles.

MadWeight

MadWeight [31] is a package, built on top of MadGraph, to find the Matrix Element weight of experimental events for a large set of processes. This procedure, also called the Matrix Element method, is aimed at determining a set of free parameters α of a given theory from a data sample. It maximizes the information that can be extracted from the detector by defining for each observed event \mathbf{x} a conditional weight $P(\mathbf{x}|\alpha)$ that quantifies the agreement between the theoretical model with parameters α and the experimental event \mathbf{x} . In the definition of the weights, the parton-level high-energy collision is factorized from the detector-level event, by introducing the parton-level configuration \mathbf{y} with a weight given by the squared matrix element $|M_\alpha(\mathbf{y})|^2$. The evolution of this parton-level configuration \mathbf{y} into a reconstructed event \mathbf{x} in the detector is taken into account by a transfer function $W(\mathbf{y}, \mathbf{x})$. As a result, the weight of a specific

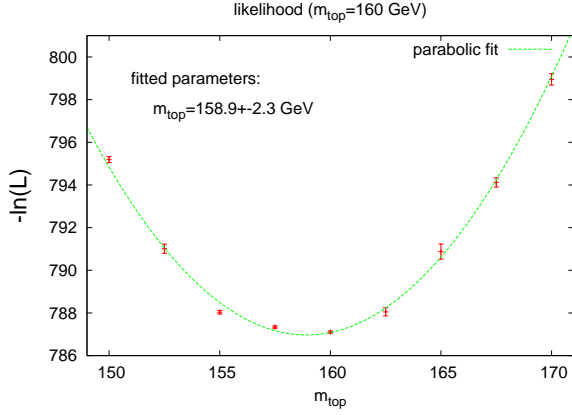


FIGURE 2. Extraction of the top quark mass from a sample of 20 Monte Carlo $t\bar{t}$ events (semi-leptonic channel).

event \mathbf{x} is of the form

$$P(\mathbf{x}|\alpha) = \frac{1}{\sigma_\alpha} \int d\phi(\mathbf{y}) |M_{\alpha(\mathbf{y})}|^2 \times dw_1 dw_2 f_1(w_1) f_2(w_2) W(\mathbf{x}, \mathbf{y}),$$

where $f_1(w_1)$ and $f_2(w_2)$ are the parton distribution functions. The normalization by the total cross section σ_α ensures that $P(\mathbf{x}|\alpha)$ is a probability density. Once the probability density $P(\mathbf{x}_i|\alpha)$ has been computed for each event \mathbf{x}_i , the most likely value for α can be obtained through a likelihood maximization method.

The numerical evaluation of the weights $P(\mathbf{x}|\alpha)$ is in general very complicated, since both the squared matrix element and the transfer function are highly non-uniform over the phase space. For an efficient Monte Carlo integration, phase-space points must be generated according to the peak structure of the integrand. Therefore, a specific phase-space generator, tuned to the shape of the transfer function and the squared matrix element, is required. MadWeight decomposes the phase space topology into substructures, where an efficient integration can be achieved through suitable parametrizations.

Fig 2 provides an example of result that can be obtained with MadWeight. The top-quark mass is extracted from a (MC) sample of 20 $t\bar{t}$ events with one lepton in the final state, with $m_t = 160$ GeV in the simulation. The weights are computed with MadWeight and combined to get the likelihood displayed in Fig. 2. The value of the reconstructed mass of the top quark is 158.9 ± 2.3 GeV.

The types of processes that MadWeight can be used for include any pair-production processes with decay chains. Also processes with three or more particles produced in the central interaction can be handled, such as pair production processes with radiation of an additional parton. This provides for a large versatility and will allow for

Matrix Element methods to be used for many new types of processes.

MadDipole

MadDipole [32] is a tool for automatic calculation of dipole-subtracted real corrections to next-to-leading order calculation. Any next-to-leading (NLO) computation in QCD includes the calculation of real contributions, with the emission of an additional parton, and virtual contributions, also called loop terms. In general these suffer from soft and/or collinear singularities, which only cancel after all contributions are summed. Because the real contributions have one more particle in the final state, numerical integrations over the phase spaces of the real and virtual contributions need to be done independently, and hence the divergencies must be extracted in a form where their cancellation is explicit. One solution to remove the divergences due to the phase space integration in the real contribution, is the subtraction scheme proposed by Catani and Seymour [45]. In this method, the Born contribution times a dipole function is added to both the real and the virtual contributions, schematically

$$\sigma^{\text{NLO}} = \int_{m+1} \left[d\sigma^{\text{real}} - d\sigma^{\text{Born}} \otimes D \right] + \int_m \left[\int_{\text{loop}} d\sigma^{\text{virt.}} + \int_1 d\sigma^{\text{Born}} \otimes D \right]_{\epsilon=0},$$

where $d\sigma^{\text{real}}$, $d\sigma^{\text{Born}}$ and $d\sigma^{\text{virt.}}$ are the real, Born and virtual matrix elements, respectively, and D is the dipole function. The dipole functions are defined in such a way that the real term plus subtraction term and the virtual plus subtraction term are separately finite, and the contributions from the subtraction terms cancel in the sum of the real and virtual contributions.

MadDipole fully automatizes the calculation of the dipole subtraction terms for massless and massive partons in the MadGraph/MadEvent framework. The implementation is done in such a way that the user only needs to specify the desired $(n+1)$ -particle process, and MadDipole then returns a Fortran code for calculating all dipoles, combined with possible Born processes which can lead to the $(n+1)$ process specified by the user. This works for processes in any model. An implementation for automation of the calculation of subtraction terms also for the virtual contributions is underway.

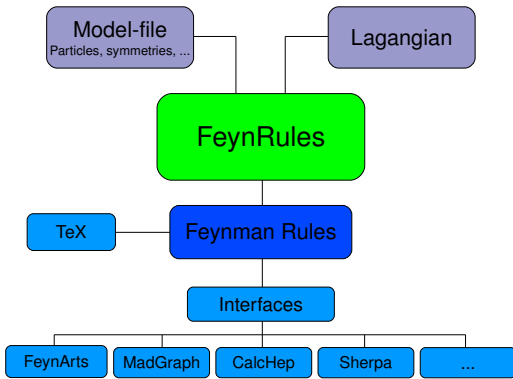


FIGURE 3. Logical organization of FeynRules.

Interface to FeynRules

FeynRules [22] is a new package based on *Mathematica*¹ which takes a model file with the Lagrangian as input and derives the interaction vertices associated with this Lagrangian. The underlying algorithm, based on canonical quantization formalism, is suitable not only for renormalizable theories, but allows the derivation of the Feynman rules in effective theories involving higher-dimensional operators as well, which makes the package a useful tool for developing models containing the SM as a low-energy effective theory.

The basic input a user provides when implementing his/her model into FeynRules is the so called model file, a text file containing all the properties of the model (particles, parameters, etc.), and the Lagrangian written down using standard *Mathematica* commands, augmented by some new symbols like Dirac matrices, which are necessary when writing down a Lagrangian. The information contained in the model file, together with the interaction vertices computed inside *Mathematica*, are stored in a generic format which is suitable for any further processing of this information. In a second step, FeynRules can translate this generic model (with the vertices) into the model format of choice and allows in this way to implement the new model in any tool for which such an interface exists. The organization of FeynRules is visualized in Fig. 3.

This approach allows FeynRules to go beyond previous packages with similar functionality in several ways:

1. FeynRules is not tied to any existing Feynman diagram calculator.
2. The generic model format of FeynRules is suitable to be translated to any other format.

3. The user may choose his favorite Feynman diagram calculator, according to the strength and advantages of the latter.
4. The underlying *Mathematica* structure allows a “theorist-friendly” environment, which makes the package useful as a “sandbox” to develop new models.

Currently, interfaces have been written for CalcHEP/CompHEP, FeynArts/FormCalc, MadGraph/MadEvent and Sherpa, and more interfaces will be added in the future.

Several models have been implemented in order to validate the code, and extensive testing to check the interfaces is currently ongoing both between the output of different Matrix Element generators using the results of FeynRules-generated inputs and previously implemented models. In particular the Standard Model and a higgsless three-site model have been carefully checked in this way, to ensure the correctness of the package, and further checks are ongoing for the MSSM and extradimensional models.

CONCLUSIONS

With the recent developments of, and additions to, MadGraph/MadEvent, the package has taken several further steps towards a full-fledged simulation tool for physics beyond the Standard Model. These developments include, in particular, the FeynRules package which allows easy implementation of any new model into MG/ME; calculation of decay widths and decays for any model, either using the external BRIDGE package [44] or MG/ME directly; simulation of decay chain events, keeping full spin correlations and finite width effects; matching of jets between MG/ME multiparton generation and Pythia parton showers; and not least the analysis of data events using matrix element techniques. MG/ME can now furthermore be used directly as a tool for simulations of the real corrections to next-to-leading order QCD calculations for multiparticle processes in any model. Large-scale simulations can be done using the Grid with the new grid-pack functionality, which is especially important for Standard Model background event generation.

The MadGraph/MadEvent philosophy includes a strong emphasis of building a user community, not only through fast response to questions and bugs, but also by continuously develop the software and implement requested features and functionalities. We also welcome and support external efforts such as model implementations and development of external packages and tools. And not least, we provide public clusters with personal process databases, a Twiki site for communication, an

¹ *Mathematica* is a registered trademark of Wolfram Research, Inc.

open CVS repository and, naturally, completely open source code.

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REFERENCES

1. T. Gleisberg, et al., *JHEP* **02**, 056 (2004), hep-ph/0311263.
2. T. Sjostrand, S. Mrenna, and P. Skands, *Comput. Phys. Commun.* **178**, 852–867 (2008), arXiv:0710.3820.
3. S. Gieseke, A. Ribon, M. H. Seymour, P. Stephens, and B. Webber, *JHEP* **02**, 005 (2004), hep-ph/0311208.
4. M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, *JHEP* **07**, 001 (2003), hep-ph/0206293.
5. E. Boos, et al., *Nucl. Instrum. Meth.* **A534**, 250–259 (2004), hep-ph/0403113.
6. A. Pukhov (2004), hep-ph/0412191.
7. A. Kanaki, and C. G. Papadopoulos, *Comput. Phys. Commun.* **132**, 306–315 (2000), hep-ph/0002082.
8. W. Kilian, T. Ohl, and J. Reuter (2007), arXiv:0708.4233.
9. J. Alwall, et al., *JHEP* **09**, 028 (2007), arXiv:0706.2334.
10. J. M. Campbell, and R. K. Ellis, *Phys. Rev.* **D62**, 114012 (2000), hep-ph/0006304.
11. S. Frixione, and B. R. Webber (2006), hep-ph/0612272.
12. T. Stelzer, and W. F. Long, *Comput. Phys. Commun.* **81**, 357–371 (1994), hep-ph/9401258.
13. H. Murayama, I. Watanabe, and K. Hagiwara (1992), KEK-91-11.
14. F. Maltoni, and T. Stelzer, *JHEP* **02**, 027 (2003), hep-ph/0208156.
15. J. Alwall, et al., *Comput. Phys. Commun.* **176**, 300–304 (2007), hep-ph/0609017.
16. T. Sjostrand, S. Mrenna, and P. Skands, *JHEP* **05**, 026 (2006), hep-ph/0603175.
17. G. Corcella, et al. (2002), hep-ph/0210213.
18. J. Conway, et al. (2006), see <http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.htm>.
19. Implementation by M. Herquet and S. de Visscher (2006).
20. G. C. Cho, et al., *Phys. Rev.* **D73**, 054002 (2006), hep-ph/0601063.
21. Implementation in MadEvent by J. Alwall (2006).
22. N. D. Christensen, and C. Duhr (2008), arXiv:0806.4194.
23. J. Alwall, et al., *Eur. Phys. J.* **C53**, 473–500 (2008), arXiv:0706.2569.
24. J. Alwall, F. Maltoni, and S. de Visscher (2008), *in progress*.
25. S. de Visscher (2008), in these proceedings.
26. Implementation by J. Alwall and T. Stelzer (2007), use this publication as reference.
27. Implementation by J. Alwall (2008), use this publication as reference.
28. The MadGraph Team (2008), see <http://cp3wks05.fynu.ucl.ac.be/twiki/bin/view/Library/GridDevelopment>.
29. The MadGraph Team (2008), see <http://cp3wks05.fynu.ucl.ac.be/twiki/bin/view/Library/MadGraphSamples>.
30. P. Artoisenet, F. Maltoni, and T. Stelzer, *JHEP* **02**, 102 (2008), arXiv:0712.2770.
31. P. Artoisenet, O. Mattelaer, V. Lemaître, and F. Maltoni (2008), *in progress*.
32. R. Frederix, T. Gehrmann, and N. Greiner (2008), arXiv:0808.2128.
33. Implementation by C. Duhr and M. Herquet (2008).
34. S. Catani, F. Krauss, R. Kuhn, and B. R. Webber, *JHEP* **11**, 063 (2001), hep-ph/0109231.
35. F. Krauss, *JHEP* **08**, 015 (2002), hep-ph/0205283.
36. L. Lönnblad, *JHEP* **05**, 046 (2002), hep-ph/0112284.
37. M. Mangano, et al. (2002), see <http://mlm.home.cern.ch/mlm/alpgen/>.
38. S. Mrenna, and P. Richardson, *JHEP* **05**, 040 (2004), hep-ph/0312274.
39. J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker (2008), arXiv:0803.0019.
40. J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker (2008), *in progress*.
41. J. M. Smillie, and B. R. Webber, *JHEP* **10**, 069 (2005), hep-ph/0507170.
42. A. Alves, O. Eboli, and T. Plehn, *Phys. Rev.* **D74**, 095010 (2006), hep-ph/0605067.
43. D. Berdine, N. Kauer, and D. Rainwater, *Phys. Rev. Lett.* **99**, 111601 (2007), hep-ph/0703058.
44. P. Meade, and M. Reece (2007), hep-ph/0703031.
45. S. Catani, and M. H. Seymour, *Nucl. Phys.* **B485**, 291–419 (1997), hep-ph/9605323.