

# MadGolem: automating NLO calculations for New Physics

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With the LHC close to complete its 8 TeV run, the experimental searches have already started to probe the vast beyond-the-standard Model scenery. Providing next-to-leading order (NLO) predictions for the major new physics discovery channels is therefore a most pressing request to particle phenomenologists these days. MADGOLEM is a new computational tool that automates NLO calculations of generic  $2 \rightarrow 2$  new physics processes in the MADGRAPH/GOLEM framework. In this contribution we concisely describe the structure and performance of the code, with particular focus on the generation of the renormalized one-loop amplitudes and the automatized subtraction of infrared and on-shell divergences. We briefly survey the many dedicated tests of all these aspects and outline some applications to LHC phenomenology.

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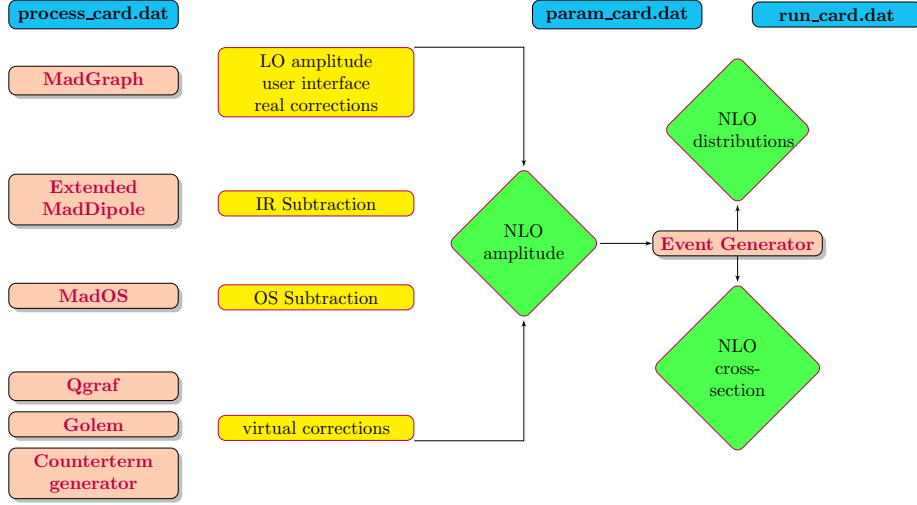
## 1. Introduction

As a result of an outstanding performance, the LHC has already delivered around  $15 \text{ fb}^{-1}$  of data at the ATLAS and CMS detectors, setting out on the quest for signatures of new physics. Direct searches rely on the pairwise production of novel heavy states or, alternatively, on their associated production along with SM degrees of freedom. Just to mention one example, the studies conducted so far have already enabled to constrain the phenomenologically viable parameter space of the Minimal Supersymmetric Standard Model (MSSM), mainly upon analyses based on jet production from squark and gluino decays plus missing energy. Accurate predictions, including next-to-leading order (NLO) QCD corrections, are thus instrumental at this stage. They allow to reduce the theoretical uncertainty, as they render more stable results with respect to the (unphysical) renormalization and factorization scale choices; on the other hand, they provide suitable total rates to normalize the event samples simulated by standard Monte Carlo (MC) generators. In this context, the development of dedicated tools that automate this type of computations ranks very high in the phenomenologists' wishlist. The community has witnessed an impressive thrust of activity in the recent years and achieved very significant milestones, cf. e.g. [1, 2, 3].

MADGOLEM [1, 2] is conceived as a highly modular, independent add-on to the major MC generator MADGRAPH [4]. It implements an automated framework in which to compute total cross sections and distributions, including QCD quantum effects to NLO accuracy. MADGOLEM is mainly tailored to describe the production of heavy particle pairs within theories beyond the SM. The tool is currently undergoing a final testing phase, prior to its public release, and is meant to be of interest for model-builders, phenomenologists and fundamentally for the LHC experimental community.

## 2. Code structure

A schematic picture of the flowchart and the inner architecture of MADGOLEM we display in Figure 1. The tree-level matrix elements (i.e. the leading order  $2 \rightarrow 2$  ones as well as the  $2 \rightarrow 3$  contributions from real emission) we obtain via MADGRAPH 4.5 [4]. The one-loop Feynman diagrams we generate via QGRAF [5]. The latter we translate and further process through a dedicated chain of PERL, FORM and MAPLE routines that handle the corresponding color, helicity and tensor structures. Spinors we manipulate algebraically resorting to spinor-helicity methods [6], while we deal with color algebra by means of a conventional color flow decomposition technique [7]. Tensor structures we decompose via a modified Passarino-Veltman scheme in the framework of GOLEM [8]. Both ultraviolet (UV) and infrared (IR) singularities from the loop integrals we regulate employing the standard 'tHooft-Veltman dimensional regularization prescription in  $n = 4 - 2\epsilon$  dimensions. In order to handle these one-loop corrections we stick to a fully analytical, Feynman-diagrammatic approach. The explicit analytical form of the one-loop amplitudes we keep accessible at all the stages throughout the entire calculation. The final expression we cast in terms of partial amplitudes, each of them consisting of i) one coefficient, which depends on the coupling constants, masses and kinematic invariants; and ii) a basis of fundamental color and helicity structures, as well as of one-loop integrals. The latter we evaluate numerically with the aid of ONELOOP [9].

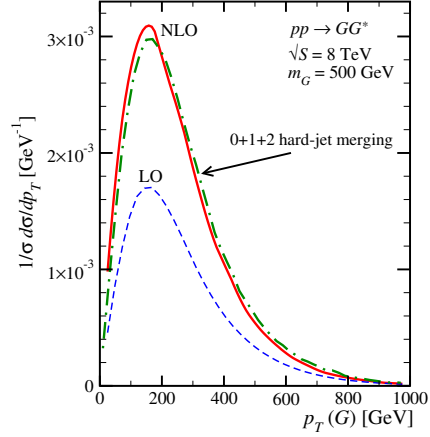


**Figure 1:** Modular structure of MADGOLEM.

A major building-block of MADGOLEM concerns the automated handling of the different divergent contributions, which are ubiquitous in higher order calculations. UV divergences, on the one hand, we renormalize by means of corresponding UV counterterms, which we generate via MADGRAPH 4.5 [4] alongside the tree-level amplitudes. These counterterms we write in terms of  $\mathcal{O}(\alpha_s)$ , model-dependent 2-point functions which we supply as a separate library. We use the  $\overline{\text{MS}}$  scheme with decoupled heavy colored states [10] for the renormalization of the strong coupling constant  $\alpha_s$ , while the particle masses we renormalize on-shell. If applicable, supersymmetry-restoring counterterms are conveniently included at this point [11]. Catani-Seymour (CS) dipoles we introduce to subtract the collinear and soft singularities [12]. We implement them as a generalization to the MADDIPOLE package [13], including the novel massive dipoles needed to cope with the IR structures of the non-standard heavy colored particles (e.g. squarks, gluinos or sgluons, among others). We retain the explicit dependence on the FKS-like  $\alpha$  phase space cutoff [14]. In so doing we explicitly track down the separation of the soft and collinear regions that are subsumed into the integrated dipoles – and so into part of the virtual corrections – and those which constitute the genuine contribution to the  $2 \rightarrow 3$  real emission terms. Additionally, on-shell (OS) divergences may occur if the produced heavy colored particles give rise to light-quark jets, as part of the real emission corrections at NLO. These situations lead to non-integrable phase space singularities and induce a potential double counting, if effectively treated as part of the NLO effects. We adopt the PROSPINO scheme [15] to subtract these singularities locally and sidestep the mentioned double counting, a strategy that preserves gauge invariance and spin correlations.

Finally, we interface all these different modules and translate the resulting analytical output into Fortran code, which we can further run numerically to obtain the NLO total rates and distributions. A user-friendly interface is exported from MADGRAPH. The model parameters, collider setup and numerical arrangements can be specified by the user via a set of input cards, again following the familiar MADGRAPH environment. The structure of the resulting Fortran code, in terms of independent subprocesses for the leading-order (LO), virtual and real corrections, for each of

$m_G$ [GeV]	$\sqrt{S} = 7$ TeV		
	$\sigma^{\text{LO}}$ [pb]	$\sigma^{\text{NLO}}$ [pb]	$K$
200	$1.40 \times 10^2$	$2.26 \times 10^2$	1.61
350	$4.83 \times 10^0$	$8.21 \times 10^0$	1.70
500	$4.05 \times 10^{-1}$	$7.32 \times 10^{-1}$	1.81
750	$1.48 \times 10^{-2}$	$3.01 \times 10^{-2}$	2.03
1000	$8.60 \times 10^{-4}$	$2.00 \times 10^{-3}$	2.33



**Figure 2:** Example of a phenomenological analysis carried out within MADGOLEM. We consider the production of sgluon pairs at the LHC [2]. In the left panel we show the total LO and NLO rates for different sgluon masses, alongside with the associated  $K$ -factors. In the right panel we display the LO and NLO distributions as a function of the sgluon  $p_T$ , and compare them to the results from MLM jet merging with (0+1+2) hard jets.

the different partonic subchannels, makes it particularly suitable for parallelization.

MADGOLEM is mainly oriented towards beyond the Standard Model (BSM) physics. As compared to alternative codes, such as the case of PROSPINO – specifically tailored for pair-production processes within the MSSM – MADGOLEM offers a flexible, adaptable and fully automatized platform. It enables a broad coverage of the new physics scenery, as it handles genuine BSM structures such as Majorana fermions, new IR and OS singularities stemming from heavy colored states, and effective interactions – the latter parameterized by higher dimensional operators. Currently, MADGOLEM fully supports NLO calculations within i) the SM; ii) the MSSM; iii) a number of generic new physics realizations featuring new heavy states with different color charges and spin representations (e.g. sgluons and leptogluons, among others); iv) generic extensions of the SM with higher dimensional operators (e.g. for the study of monotop signatures from dimension six operators).

The complexity of some processes, in particular those involving fermion fields with large color representations, demands for dedicated coding strategies to achieve a satisfactory performance of the tool at the different stages, in particular in terms of processing and running times. These strategies include, for instance, loop filtering; grouping of topologically equivalent diagrams; and the intensive use of dynamically-linked libraries and multithread processing.

### 3. Validation strategies and applications to phenomenology

Exhaustive cross-checks have been performed to ensure the reliability of our tool. The total NLO rates and corresponding  $K$  factors have been computed with MADGOLEM for a fairly large number of processes both within the SM and the MSSM, covering all representative possibilities of spin/color representations, interactions and topologies. The cancellation of the UV, IR and OS divergences, as well as the gauge invariance of the overall result, has been explicitly confirmed (in all cases numerically, and also analytically for some specific ones). The finite parts of the renormalized one-loop amplitudes we have contrasted against independent calculations performed

with FEYNARTS, FORMCALC and LOOPTOOLS [16]. Dedicated attention has been devoted to the numerical stability and convergence of the results, ensuring a robust implementation of the CS dipoles and the OS subtraction scheme. The specific behavior of the dipoles, as well as of the OS subtraction terms nearby the singular regions, has been carefully studied – including e.g. the aforementioned  $\alpha$ -parameter to ascertain the independence of the subtraction procedure from the arbitrary phase space regulator in use. Finally, and whenever available, we have compared the MADGOLEM outcomes to independent results presented in the literature. For the total NLO rates, in particular, we have explicitly confirmed our agreement with PROSPINO [17] for the main pair production channels within the MSSM, including the processes mediated by (SUSY)QCD (viz.  $pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}$  and  $\tilde{g}\tilde{g}$ ) and SUSY-EW interactions ( $pp \rightarrow \tilde{\chi}\tilde{\chi}, \tilde{l}\tilde{l}^*$ ). For the distributions, in turn, we have cross-checked our results with MADFKS [18].

Letting aside this extensive cross-checking program, we have also started to exploit all the MADGOLEM capabilities to conduct original phenomenology studies. On the one hand, we have considered the associated squark/neutralino production  $pp \rightarrow \tilde{q}\tilde{\chi}^0$ , which leads to a characteristic monojet +  $E_T$  signature [1]; likewise, we have addressed the pair production of new exotic states with higher color representations, in particular the case of scalar  $SU(3)_C$  adjoints – the so-called sgluons [2]. A number of further applications are also underway, in particular a comprehensive study of the pairwise production of squarks and gluinos [19], which spells out the improved capabilities of MADGOLEM with respect to the presently available tools [15].

All these analyses thus qualify as pioneering examples of totally automated NLO calculations in a wide variety of new physics scenarios. MADGOLEM enables to perform very detailed phenomenological studies of pair production processes beyond the SM, including i) the calculation of the total NLO rates and corresponding  $K$  factors; in the case of the MSSM, for instance, it is possible to undertake a comprehensive survey along the parameter space of the model [19], as no restrictions on the SUSY mass spectrum nor the couplings are assumed beforehand – at variance with alternative codes; ii) a detailed analysis of the virtual and the real NLO quantum corrections – as the different contributions from all the subchannels and one-loop topologies are accessible separately; iii) the study of the dependence with respect to the renormalization and factorization scale choices, and so of the theoretical uncertainties and how these nail down when comparing the NLO predictions to the mere LO ones; iv) and perhaps most significantly, MADGOLEM supports the generation of NLO distributions. Interestingly enough, further comparisons to the results obtained via multi-jet merging [20] can be easily carried out in the MADGRAPH framework. These nicely confirm that the matched samples with extra hard jets correctly reproduce the kinematical features of colored heavy particle production, while the total NLO rates from the fixed-order calculation can be taken as a suitable normalization for the corresponding event samples. In Figure 2 we illustrate some of these features for the particular case of sgluon pair production  $pp \rightarrow GG^*$  at the LHC [2].

In summary, MADGOLEM completely automates the calculation of NLO QCD corrections to generic BSM pair production processes, as well as their interface to the standard Monte Carlo generator MADGRAPH. The tool resorts to a fully analytical, Feynman-diagrammatic approach and is endowed with all the technical machinery needed to automatically handle the UV, IR and OS singularities and to retrieve the total NLO cross-sections and corresponding  $K$ -factors, as well as

distributions. MADGOLEM represents a new step forward in this automation program which sets sights, after all, on extending solid bridges between theory and experiments.

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