New developments in MADLOOP

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In this talk, the recent developments of MADLOOP are presented. MADLOOP automates the computation of one-loop QCD corrections to an arbitrary scattering process in the Standard Model. I first review the current version of the code which has been made *public* through the AMC@NLO webpage. In the second part, progress in the implementation of MADLOOP within the MG5 framework is presented along with the preliminary speed benchmarks for a few selected massless QCD processes.

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1. MADLOOP **in a nutshell**

Recently, several programs [1, 2, 3, 4, 5, 6] for the computation of one-loop corrections in QCD have been developed thanks to a new generation of tools based on numerical [7, 8] or semi-analytical [1, 2, 3, 5] reduction mechanisms. MADLOOP [4] exploits the OPP [9] method as implemented in CUTTOOLS [7] and aims at the full automation of arbitrary 1-loop computations. In its original version MADLOOP is an independent C++ code interfaced to MADGRAPH4 [10] for tree-diagram generation that writes out a fortran code computing the amplitude as requested by a user. Recently, `python` version five of MADGRAPH, dubbed MG5 [11], has been released and the possibility of rewrting MADLOOP in this framework has arisen. We refer to this new version as MADLOOP5, as opposed to the original MADLOOP4 which is now part of the AMC@NLO framework and has already sucessfully provided virtual amplitudes for several calculations and LHC phenomenological applications [12, 13, 14, 15].

What follows gives a quick description of the MADLOOP program.

1.1 Program overview

The user process $\{n_i\} \rightarrow \{n_f\}$ is specified in an order file compliant with the *LesHouches* standards [16], as well as the model name and the desired QED order. The Born diagrams are generated along with the necessary counterterms (UV renormalization and the so-called R2 terms [17]). The loop topologies are constructed starting from their corresponding L-cut diagrams, which are obtained by cutting[1] the loop at a given internal line. L-cut diagrams are obtained by generating the tree-level diagrams of the process $\{n_i\} \rightarrow \{n_f\} + \{q^\star, \bar{q}^\star\}$, where the $q^\star$ are the L-cut particles, namely those that can run in the loop. For QCD corrections, it is enough to consider for $q^\star$ the gluon and all the quarks.

As loops can be cut at as many places as there are loop propagators times two (they can be read along two opposite directions), many L-cut diagrams correspond to the same loop diagram once the two L-cut particles are sewed back together. The first task of MADLOOP is to efficiently identify double counting by associating to each L-cut diagram a tag which is unique to each loop diagram contributing to the process.

Accounting for the color structure of the amplitude is a straight-forward extension of what is done at the tree-level except for the fact that in this case virtual-Born interference terms must be considered. The computation of the L-cut diagrams is carried on exactly as for tree-level processes through chains of HELAS [18] calls. However, in order to provide the integrand necessary for CUT-TOOLS to numerically evaluate the loop contribution, some modifications to the tree-level output are necessary:

- The momentum flowing in the loop is complex.

- Only the numerator of the propagator of the loop particles must be computed.

- The Lorentz trace of the loop is realized by summing over the arbitrary polarization vectors of the L-cut particles, for which an orthogonal basis is used.

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[1]These cuts have nothing to do with unitarity cuts and this is why they are referred to as *L-cuts*, standing for Loop cuts.

To assess the sanity of the result, two checks are automatically performed: the coefficient of the double pole of the virtual amplitude is compared against its universal analytical expression taken from eq. B.2 of ref. [19] and, in case a gluon or a photon are present in the external state, gauge invariance is tested by calculating the 1-loop amplitude with a longitudinal polarization.

A key issue in automatic computations is the detection and efficient management of possible numerical instabilities. Phase space points for which CUTTOOLS detects that some loops are numerically unstable, called UPS points further then, do undertake a "rescue" process at the helicity level. If the kinematical configuration of the UPS is slightly modified, it is likely that it will fall back in a stable regime. The following *shift* is applied[2]:

$$k_i^3 \longrightarrow (1+\lambda_\pm)k_i^3 \,. \tag{1.1}$$

The transverse momenta are left invariant, and the energy components are adjusted so to impose on-shellness and four-momentum conservation. If, for at least two of these modified phase-space points, the result for the originally unstable loop is flagged stable, the evaluation of the finite part of the virtual returned by MADLOOP is based on the average of the stable evaluations of the two shifted phase-space points, normalized by their respective Born amplitude. The uncertainty due this procedure is deduced from the distance between these two shifted results. Among all the processes presented in ref. [4] only a couple have a fraction of UPS larger than 10^{-4} of which 99.9% are recovered to stability after shifts of magnitude $|\lambda| = 0.01$ or $|\lambda| = 0.05$ at most. For the very few UPS still unstable after the shifts, MADLOOP returns a value based on the median of the distribution of all previous stable evaluations. This rescue system can guarantee an uncertainty due to UPS much smaller than the Monte-Carlo one for all processes presented in [4], where the interested reader can also find more details on the rescuing method.

2. Public use of MADLOOP4

The use of MADLOOP4 has recently been made public[3] through the website *amcatnlo.web.cern.ch* under the section 'Compare with MadLoop'. For a wide range of processes in the Standard Model, the user can obtain the numerical evaluation of the finite part and poles of the virtual amplitude squared against the Born one and summed over color and helicity. The only inputs required by the user are:

- The process, specified using the MADGRAPH naming conventions and compliant with the MADLOOP4 limitations (see further).

- The QED coupling order of the process.

- Wether to consider the bottom quark massive or massless.

At this stage, the input process must still respect all MADLOOP4 constraints listed below:

- The process must have a contribution at tree-level (Born level).

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[2]The shift of Eq. 1.1 is performed along the z-axis but other directions are also considered.

[3]The user still needs to register on the webpage before using this tool. The registration process, automatic and fast, is only here to keep track of the different users of the tool.

- The Born Feynman diagrams contributing must not comprehend any 4-gluon vertex.

- All Born contributions must factorize the same powers of α_s and α.

- At least one quark must be present in the external states of the input process.

The conventions adopted by MADLOOP4 for the computation are:

- UV renormalization is included, in the $\overline{MS}$ scheme for massless modes and using zero-momentum subtraction for the massive ones. See appendix B.2 of ref. [4] for the definition of the UV counterterms employed.

- The widths of all particles are set to zero as MADLOOP4 does not work in the complex mass scheme.

- The identical final state particle factor is included.

The result V is given in the CDR regularization scheme and in the form of three coefficients[4] c_0, c_{-1} and c_{-2} defined as follows:

$$V = \frac{(4\pi)^\varepsilon}{\Gamma(1-\varepsilon)}\left(\frac{c_{-2}}{\varepsilon^2} + \frac{c_{-1}}{\varepsilon} + c_0\right). \tag{2.1}$$

The model parameters used can be found on the AMC@NLO MADLOOP check webpage.

3. Recent progresses in MADLOOP5

As advertised in the introduction, MADLOOP has recently been implemented in the MG5 framework. Thanks to the great flexibility of MG5, MADLOOP5 already brings new improvements.

Firstly, MADLOOP5 generates loop-diagrams much faster thanks to the more efficient MG5 algorithm for tree-diagram generation. Moreover, all MADLOOP4 limitations listed in section 2 are relieved. The cumbersome computation of the four gluons R2 counterterm is made possible by exploiting the UFO [20] model format which allows for vertex definitions with entangled color and Lorentz structures. As a secondary upgrade, the loop diagrams themselves can now be drawn and not only the L-cut diagrams as it was the case in MADLOOP4. Figure 1 shows a snapshot of the drawings of loop diagrams contributing to the $d\,\bar{d} \to u\,\bar{u}$ process. Finally, a more efficient caching of the HELAS wavefunctions computed during the evaluation of a phase-space point improves running time.

In the near future, MADLOOP5 will also feature other new capabilities. This includes the ability of working in the complex mass scheme and to have massive electroweak bosons running in the loop. For this to be useful, mixed order perturbation corrections will be supported[5]. To more efficiently handle numerically unstable phase-space points, MG5 will be able to provide the loop integrand to CUTTOOLS in multiple-precision when needed. Finally, decay chains will be

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[4]Notice that if any contributing Born diagram contains a massive virtual quark (i.e. on an internal line of the Feynman Diagram), only the coefficient c_0 and c_{-2} are correctly computed and c_{-1} will not be provided.

[5]MG5 can already generate the relevant loop for processes for which the user includes the perturbation of different coupling orders, like QCD and QED.
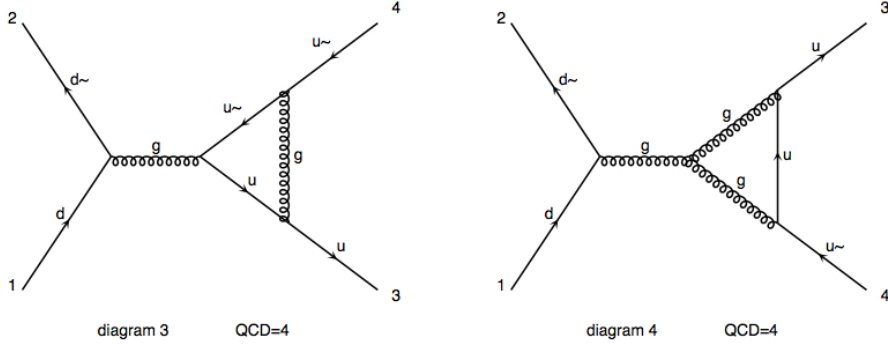
Figure 1: Two examples of loop Feynman diagrams drawn by MADLOOP5 for the process $d\,\bar{d} \to u\,\bar{u}$.

Process	Generation time		Output size		Running time	
	ML5	ML4	ML5	ML4	ML5	ML4
$d\bar{d} \to u\bar{u}$	8.8s	5.4s	208 Kb	268 Kb	0.0088s	0.0094s
$d\bar{d} \to d\bar{d}g$	17s	104s	424 Kb	1.7 Mb	0.64s	0.74s
$d\bar{d} \to d\bar{d}u\bar{u}$	23s	2094s	552 Kb	3.3 Mb	1.93 s	2.34s
$gg \to ggg$	71 s	X	1.5 Mb	X	30s	X
$gg \to gggg$	37m60s[6]	X	27 Mb	X	1h12m	X

Table 1: Speed benchmark comparing results for chosen processes obtained with MADLOOP5 and MAD-LOOP4 on a machine with a dual 2.8 Ghz Intel Core CPU. The running time refers to the computation of the loop amplitude squared (against the Born) *summed over color and helicity configurations* for a single phase-space point. In particular, only the vanishing helicity configurations are filtered out, not the vanishing loops for specific helicity configurations. CUTTOOLS is allowed to re-perform the reduction in multiple-precision when needed. The reference model used here is massless QCD with two light-flavored quarks. The output file size includes the HELAS source only for MADLOOP5 as it is process independent for MADLOOP4 (no optimization is performed to get rid of the unused subroutines). The five- and six-gluon amplitudes are marked with a cross for MADLOOP4 as they are not available.

specified and generated in the exact same way as they are now for tree-level processes in MG5. In a further future, MADLOOP5 will be capable of working in any BSM models obtained directly from FEYNRULES [21].

First results from MADLOOP5 are already available for the massless QCD model with 2 light flavor quarks. Table 1 shows a comparison between results obtained with MADLOOP4 and MADLOOP5 for chosen processes. The five- and six-gluon amplitude were successfully cross-checked against the NGLUON [22] code. Drastic improvement in generation time and output file size is obtained while running time is only moderately improved.

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[6]Compilation time dominates here as gfortran takes 3h30 to compile the output code.

4. Conclusion

In the first section, the public version of MADLOOP4 with the details of its computational setup and limitations were presented. Applications to physics studies and its use as robust benchmark for other private computations have already proven to be useful.

In the last section, the preliminary results for the MADLOOP implementation in MG5 were shown along with the new features already implemented and yet to come. This paves the way to a whole set of new applications using MG5 for LHC phenomenology.

5. Acknowledgements

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