Automated next-to-leading order predictions for new physics at the LHC: The case of colored scalar pair production

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We present for the first time the full automation of collider predictions matched with parton showers at the next-to-leading accuracy in QCD within non-trivial extensions of the Standard Model. The sole inputs required from the user are the model Lagrangian and the process of interest. As an application of the above, we explore scenarios beyond the Standard Model where new colored scalar particles can be pair produced in hadron collisions. Using simplified models to describe the new field interactions with the Standard Model, we present precision predictions for the LHC within the MADGRAPH5_aMC@NLO framework.

I. INTRODUCTION

Motivated by the conceptual issues accompanying the Standard Model, many new physics theories have been developed over the last decades. Most of them exhibit an extended colored sector and related new phenomena are expected to be observable at high-energy hadron colliders such as the LHC. In particular, effects induced by hypothetical colored scalar particles have received special attention from both the ATLAS and CMS collaborations.

Many LHC analyses are indeed seeking for the scalar partners of the Standard Model quarks (the squarks) and gluons (the sgluons) that are predicted, for instance, in minimal [1,2] and non-minimal [3,4] supersymmetric or in vector-like confining theories [5].

In this context, it is clear that an approach to precision predictions that is fully general in any considered theory is highly desirable, and the MADGRAPH5_aMC@NLO framework [6] is in a prime position to provide it. Its structure for tackling leading-order (LO) computations has indeed already proved to be very efficient at satisfying the needs of both the theoretical and experimental high energy physics communities. Generalizing this flexibility to the next-to-leading order (NLO) case is however not straightforward, essentially because of the necessity of specifying model-dependent counterterms, including those arising from the renormalization of the Lagrangian. Recent developments [7] in the FEYNRULES package [8] have allowed to overcome this main obstacle and paved the way to the full automation of NLO QCD predictions matched to parton showers for generic theories.

We describe the details of this implementation by working through two specific cases and revisit some LHC phenomenology associated with stops and sgluons in the context of simplified models of new physics [9,10]. Employing state-of-the-art simulation techniques, we match matrix elements to the NLO in QCD to parton showers and present precision predictions for several kinematical observables after considering both the production and the decay of the new particles. In more detail, we make use of FEYNRULES to implement all possible couplings of the new fields to quarks and gluons and employ the NLOCT program [7] to generate a UFO module [11] containing, in addition to tree-level model information, the ultraviolet and R2 counterterms whenever the loop integral numerators are computed in four dimensions, as in MADLOOP [12] that uses the Ossola-Papadopoulos-Pittau (OPP) reduction formalism [13]. This UFO library is then linked to the MADGRAPH5_aMC@NLO framework which is used, for the first time, for predictions in the context of new physics models featuring an extended colored sector. We focus on the pair production of the new states at NLO in QCD. Their decay is then taken into account separately, at the leading order and with the spin information retained, by means of the MADSpin [14] and MADWIDTH [15] programs.

In the rest of this paper, we first define simplified models describing stop and sgluon dynamics and detail the renormalization of the effective Lagrangians and the validation of the UFO models generated by NLOCT. Our results follow and consist of total rates and differential distributions illustrating some kinematical properties of the produced new states and their decay products.

II. BENCHMARK SCENARIOS FOR STOP HADROPRODUCTION

Following a simplified model approach, we extend the Standard Model by a complex scalar field (a stop) of mass . This field lies in the fundamental representation of SU(3)c, so that its strong interactions are standard and embedded into SU(3)c-covariant derivatives. We enable the stop to decay via a coupling to a single top quark and a gauge-singlet Majorana fermion of mass that can be identified with a bino in complete supersymmetric models. Finally, despite of being
allowed by gauge invariance, the single stop couplings to down-type quarks, as predicted in $R$-parity violating supersymmetry, are ignored for simplicity. We model all considered interactions by the Lagrangian

$$L_3 = D_\mu \sigma_3^A D^\mu \sigma_3 - m_3^2 \sigma_3^A \sigma_3 + i \frac{g_2}{2} \Phi \chi - \frac{1}{2} m_\chi \bar{\chi}\chi + \left[ \sigma_3^A (\bar{g}_L P_L + \bar{g}_R P_R) \chi + h.c. \right],$$

where we denote the strengths of the stop couplings to the fermion $\chi$ by $\bar{g}$ and $P_{L,R}$ are the left- and right-handed chirality projectors.

Aiming to precision predictions at the NLO accuracy, a renormalization procedure is required in order to absorb all ultraviolet divergences yielded by virtual loop-diagrams. This is achieved through counterterms that are derived from the tree-level Lagrangian by replacing all bare fields (generically denoted by $\Psi$) and parameters (generically denoted by $A$) by

$$\psi \rightarrow Z_{\psi}^{1/2} \psi \approx \left[ 1 + \frac{1}{2} \delta Z_{\psi} \right] \psi \quad \text{and} \quad A \rightarrow A + \delta Z_A,$$

where the renormalization constants $\delta Z$ are restricted in our case to QCD contributions at the first order in the strong coupling $\alpha_s$. Like in usual supersymmetric setups, the $\bar{g}$ couplings are of a non-QCD nature so that our simplified model does not feature new strong interactions involving quarks. The wave-function renormalization constant of the latter is therefore unchanged with respect to the Standard Model, contrary to the gluon one that must appropriately compensate stop-induced contributions. Adopting the on-shell renormalization scheme, the gluon and stop wave-function ($\delta Z_g$ and $\delta Z_{\sigma_3}$) and mass ($\delta m_3^2$) renormalization constants read

$$\delta Z_g = \delta Z_{g}^{(SM)} - \frac{g_2^2}{96\pi^2} \left( 1 - \log \frac{m_3^2}{\mu_R^2} \right),$$

$$\delta Z_{\sigma_3} = 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_2^2 m_3^2}{12\pi^2} \left( \frac{3}{\epsilon} + 7 - 3 \log \frac{m_3^2}{\mu_R^2} \right),$$

where $\delta Z_{g}^{(SM)}$ collects the Standard Model components of $\delta Z_g$. Moreover, we denote the renormalization scale by $\mu_R$ and following standard conventions, the ultraviolet divergent parts of the renormalization constants are written in terms of the quantity $\frac{1}{\epsilon} = 1/\epsilon - \gamma_E + \log 4\pi$ where $\gamma_E$ is the Euler-Mascheroni constant and $\epsilon$ is linked to the number of space-time dimensions $D = 4 - 2\epsilon$.

The renormalization of the strong coupling is achieved by subtracting, at zero-momentum transfer, all heavy particle contributions from the gluon self-energy. This ensures that the running of $\alpha_s$ solely originates from $n_f = 5$ flavors of light quarks and gluons, and any effect induced by the massive top and stop fields is decoupled and absorbed in the renormalization constant of $\alpha_s$,

$$\frac{\delta \alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi \epsilon} \left[ \frac{n_f}{3} - \frac{11}{2} \right] + \frac{\alpha_s}{6\pi} \left( \frac{1}{\epsilon} - \log \frac{m_t^2}{\mu_R^2} \right) + \frac{\alpha_s}{24\pi} \left( \frac{1}{\epsilon} - \log \frac{m_\chi^2}{\mu_R^2} \right),$$

All loop-calculations achieved in this work rely on the OPP formalism. It is based on the decomposition of any loop amplitude in both cut-constructible and rational elements, the latter being related to the $\epsilon$-pieces of the loop-integral denominators ($R_1$) and numerators ($R_2$). For any renormalizable theory, there is a finite number of $R_2$ terms, and they all involve interactions with at most four external legs that can be seen as counterterms derived from the tree-level Lagrangian. Considering corrections at the first order in QCD, the $\sigma_3$-field induces three additional $R_2$ counterterms with respect to the Standard Model case,

$$R_2^{\sigma_3 \sigma_3} = \frac{i g_2^2}{72\pi^2} \delta_{c_1 c_2} \left[ 3m_3^2 - \mu^2 \right],$$

$$R_2^{g g \sigma_3} = \frac{53i g_2^2}{376\pi^2} T_{c_2 c_3} (p_2 - p_3)^{\mu_1},$$

$$R_2^{g g g} = \frac{i g_2^2}{1152\pi^2} \eta^{\mu_1 \mu_2} \left[ 3\delta_{a_1 a_2} - 187 \{ T_{a_1}, T_{a_2} \} \right]_{c_3 c_4},$$

where $c_i$, $\mu_i$, and $p_i$ indicate the color index, Lorentz index, and the four-momentum of the $i$th particle incoming to the $R_2$ vertex, respectively. Moreover, the matrices $T$ denote fundamental representation matrices of SU(3).

Contrary to complete supersymmetric scenarios, the $\bar{g}$ operators present a non-trivial one-loop ultraviolet behavior that is not compensated by effects of other fields such as gluinos. Since we focus on QCD NLO corrections to the strong production of a pair of $\sigma_3$ fields followed by their LO decays, the related counterterms are therefore omitted from this document.

Our stop simplified model has been implemented in FeynRules, and we have employed the NLoCT package to automatically generate all QCD ultraviolet and $R_2$ counterterms (including the Standard Model ones). The output has been validated against our analytical calculations, which constitutes a validation of the handling of new massive colored states by NLoCT. Finally, the analytical results have been exported to a UFO module that we have imported into MadGraph5_aMC@NLO. For our numerical analysis, we consider scenarios where $m_3$ and $m_\chi$ are kept free. The $\bar{g}_{L,R}$ parameters are fixed to typical values for supersymmetric models featuring a bino-like neutralino and a maximally-mixing top squark,

$$\bar{g}_L = 0.25 \quad \text{and} \quad \bar{g}_R = 0.06.$$
The corresponding effective Lagrangian reads
\[ \mathcal{L}_g = \frac{1}{2} D_\mu \sigma_8 D^\mu \sigma_8 - \frac{1}{2} m_s^2 \sigma_8 \sigma_8 + \frac{g_s}{\Lambda} \sigma_8 G_{\mu \nu} G^{\mu \nu} \]
\[ + \sum_{q=u,d} \left[ \sigma_8 \bar{q} (\gamma^\mu P_L + \gamma^\mu P_R) q + \text{h.c.} \right], \]
where \( G^{\mu \nu} \) refers to the gluon field strength tensor and the single sgluon interaction strengths are denoted by \( \hat{g} \). Although the \( \hat{g} \) operators induce single sgluon production, we ignore it in this work since the presence of a loop-induced ultraviolet divergence. We postpone the associated study to a future work.

The \( \hat{g} \) couplings being technically of higher-order in QCD (as in complete theories), the quark fields are renormalized like in the Standard Model. In contrast, the sgluon QCD interactions induce a modification of the on-shell gluon wave-function renormalization constant \( \delta Z_g \) and yield non-vanishing on-shell sgluon wave-function renormalization constant \( \delta Z_{\sigma_8} \) and mass \( (m_{\sigma_8}^2) \) renormalization constants,

\[ \delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{32 \pi^2} \left[ \frac{1}{\epsilon} - \log \frac{m_{\sigma_8}^2}{\mu_R^2} \right], \]

\[ \delta Z_{\sigma_8} = 0 \quad \text{and} \quad m_{\sigma_8}^2 = -\frac{3g_s^2 m_{\sigma_8}^2}{16 \pi^2} \left[ \frac{7}{\epsilon} + 7 - 3 \log \frac{m_{\sigma_8}^2}{\mu_R^2} \right]. \]

Sgluon effects are also subtracted, at zero-momentum transfer, from the gluon self-energy and absorbed in the renormalization of the strong coupling,

\[ \frac{\delta \alpha_s}{\alpha_s} = \frac{\alpha_s}{2 \pi \epsilon} \left[ \frac{m_s}{3} - \frac{11}{2} \right] + \frac{\alpha_s}{6 \pi} \left[ \frac{1}{\epsilon} - \log \frac{m_{\sigma_8}^2}{\mu_R^2} \right] \]
\[ + \frac{\alpha_s}{8 \pi} \left[ \frac{1}{\epsilon} - \log \frac{m_{\sigma_8}^2}{\mu_R^2} \right]. \]

They finally induce new \( R_2 \) counterterms,

\[ R_2^{g_{\sigma_8}} = \frac{g_s^2}{32 \pi^2} \delta_{a_1 a_2} \left[ 3m_{\sigma_8}^2 - p^2 \right], \]

\[ R_2^{g_{\sigma_8} \sigma_8} = \frac{g_s^3}{64 \pi^2} f_{a_1 a_2 a_3} (p_2 - p_1)^{\mu_1}, \]

\[ R_2^{g_{\sigma_8} \sigma_8} = \frac{g_s^4}{384 \pi^2} \eta^{\mu_1 \mu_2} \left[ 72(d_{a_1 a_2 c} d_{a_2 a_3 c} + d_{a_1 a_3 c} d_{a_2 a_3 c}) \right. \]
\[ - 141 d_{a_1 a_2 c} d_{a_3 a_4 e} - 92 \delta_{a_1 a_2} \delta_{a_3 a_4} \]
\[ \left. + 50 (\delta_{a_1 a_3} \delta_{a_2 a_4} + \delta_{a_1 a_4} \delta_{a_2 a_3}) \right], \]

in the same notations as in the previous section.

We have implemented the sgluon simplified model in FeynRules and generated a UFO model that we have linked to MadGraph5_aMC@NLO by means of the NLOCT package. The generated model has then been validated analytically against the above results. Our numerical study relies on benchmark scenarios inspired by an \( R \)-symmetric supersymmetric setup with non-minimal flavor violation in the squark sector [17], in which the only non-vanishing coupling parameters are fixed to

\[ \frac{\hat{g}_a}{\Lambda} = 1.5 \cdot 10^{-6} \text{ GeV}^{-1}, \]

\[ (\hat{g}_{\sigma_8}^{L,R})_{3i} = (\hat{g}_{\sigma_8}^{L,R})_{33} = 3 \cdot 10^{-3} \quad \forall i = 1, 2, 3. \]

### IV. LHC PHENOMENOLOGY

In Tab. I we provide stop and sgluon pair production cross sections for LHC collisions at center-of-mass energies of \( \sqrt{s} = 8 \) and 13 TeV and for different mass choices. The results are evaluated both at the LO and NLO accuracy and presented together with the associated theoretical uncertainties. For the central values, we have

| \( m_3 \) [GeV] | \( \sigma^{LO} \) [pb] | \( \sigma^{NLO} \) [pb] | \( m_8 \) [GeV] | \( \sigma^{LO} \) [pb] | \( \sigma^{NLO} \) [pb] |
|---|---|---|---|---|---|
| 100 | 389.3 \( ^{+34.2}_{-23} \)% | 555.8 \( ^{+14.9}_{-13.5} \)% | 8 TeV | 1066 \( ^{+29.1}_{-21} \)% | 1497 \( ^{+14.1}_{-12} \)% |
| 250 | 4.118 \( ^{+44.9}_{-27} \)% | 5.503 \( ^{+13.3}_{-13.7} \)% | 15.59 \( ^{+35.2}_{-28.4} \)% | 21.56 \( ^{+12.1}_{-12.3} \)% |
| 500 | \( (6.594 \times 10^{-3})^{+35.5}_{-29.1} \)% | \( (7.764 \times 10^{-3})^{+12.1}_{-14.1} \)% | 0.3890 \( ^{+26.4}_{-26.4} \)% | 0.5062 \( ^{+12.8}_{-12.8} \)% |
| 750 | \( (3.504 \times 10^{-3})^{+4.8}_{-0.5} \)% | \( (3.699 \times 10^{-3})^{+12.3}_{-14.6} \)% | \( (3.306 \times 10^{-2})^{+41.8}_{-27.5} \)% | \( (4.001 \times 10^{-2})^{+10.8}_{-12.9} \)% |
| 1000 | \( (2.875 \times 10^{-4})^{+5.1} \)% | \( (2.775 \times 10^{-4})^{+13.6}_{-15.5} \)% | \( (4.614 \times 10^{-3})^{+46.6}_{-28.3} \)% | \( (5.219 \times 10^{-3})^{+10.9}_{-12.9} \)% |

| \( m_3 \) [GeV] | \( \sigma^{LO} \) [pb] | \( \sigma^{NLO} \) [pb] | \( m_8 \) [GeV] | \( \sigma^{LO} \) [pb] | \( \sigma^{NLO} \) [pb] |
|---|---|---|---|---|---|
| 100 | 3854 \( ^{+34.4}_{-24} \)% | 5573 \( ^{+14.9}_{-13.6} \)% | 8 TeV | 10560 \( ^{+29.2}_{-21.5} \)% | 14700 \( ^{+13.6}_{-11.9} \)% |
| 250 | 38.89 \( ^{+41.3}_{-27.7} \)% | 54.32 \( ^{+14.5}_{-14.6} \)% | 150.4 \( ^{+35.7}_{-25.1} \)% | 214.5 \( ^{+12.9}_{-2.5} \)% |
| 500 | 0.5878 \( ^{+47.6}_{-36.6} \)% | 0.7431 \( ^{+15.8}_{-16.2} \)% | 3.619 \( ^{+40.8}_{-27.0} \)% | 4.977 \( ^{+13.3}_{-14.1} \)% |
| 750 | \( (2.977 \times 10^{-2})^{+5.2}_{-3.3} \)% | \( (3.353 \times 10^{-2})^{+1.7}_{-1.7} \)% | 0.2951 \( ^{+43.6}_{-28.4} \)% | 0.3817 \( ^{+14.0}_{-14.8} \)% |
| 1000 | \( (2.328 \times 10^{-3})^{+3.3}_{-3.3} \)% | \( (2.398 \times 10^{-3})^{+1.8}_{-1.9} \)% | \( (3.983 \times 10^{-2})^{+29.5}_{-28.4} \)% | \( (4.822 \times 10^{-2})^{+16.6}_{-9.3} \)% |
We have performed independent calculations at the amplitude level.

Virtual and real contributions to sgluon-pair production are agreeing separately.

We have found to agree with our predictions.

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Similarly, we describe the hadronic activity $H_T$ associated with the production of a sgluon pair in Fig. 2 in the case of a sgluon mass of 500 GeV (red) and 1000 GeV (green).

V. CONCLUSIONS

In this Letter, we have demonstrated that a joint use of the Feyn Rules, NLOCT and MadGraph5 AMC@NLO programs enables the full automation of the Monte Carlo simulations of high-energy physics collisions at the next-to-leading order accuracy in QCD and for non-trivial extensions of the Standard Model. This has been illustrated with simplified models such as those used for supersymmetry searches at the LHC. In this context, we have adopted setups that exhibit extra colored particles and non-usual interaction structures and presented the analysis of two exemplary signals with the automated tool Mad Analysis 5.

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[1] H. P. Nilles, Phys.Rept. 110, 1 (1984)
[2] H. E. Haber and G. L. Kane, Phys.Rept. 117, 75 (1985)
[3] A. Salam and J. Strathdee, Nucl.Phys. B87, 85 (1975)
[4] P. Fayet, Nucl.Phys. B113, 135 (1976)
[5] C. Kilic, T. Okui, and R. Sundrum, JHEP 1002, 018 (2010)
[6] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, et al., JHEP 1407, 079 (2014)
[7] C. Degrande, (2014), arXiv:1406.3030 [hep-ph]
[8] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, Comput.Phys.Commun. 185, 2250 (2014)
[9] J. Alwall, P. Schuster, and N. Toro, Phys.Rev. D79, 075020 (2009)
[10] D. Alves et al. (LHC New Physics Working Group), J.Phys. C39, 105005 (2012)
[11] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, et al., Comput.Phys.Commun. 183, 1201 (2012)
[12] V. Hirschi, R. Frederix, S. Frixione, M. V. Garzelli, F. Maltoni, et al., JHEP 1105, 044 (2011)
[13] G. Ossola, C. G. Papadopoulos, and R. Pittau, Nucl.Phys. B763, 147 (2007)
[14] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, JHEP 1303, 015 (2013)
[15] J. Alwall, C. Duhr, B. Fuks, O. Mattelaer, D. G. Ozturk, et al., (2014), arXiv:1402.1178 [hep-ph]
[16] G. Ossola, C. G. Papadopoulos, and R. Pittau, JHEP 0805, 004 (2008)
[17] S. Calvet, B. Fuks, P. Gris, and L. Valery, JHEP 1304, 043 (2013)
[18] R. D. Ball, V. Bertone, S. Carrazza, C. S. Deans, L. Del Debbio, et al., Nucl.Phys. B867, 244 (2013)
[19] W. Beenakker, M. Kramer, T. Plehn, M. Spira, and P. Zerwas, Nucl.Phys. B515, 3 (1998)
[20] D. Goncalves-Netto, D. Lopez-Val, K. Mawatari, T. Plehn, and I. Wigmore, Phys.Rev. D85, 114024 (2012)
[21] T. Hahn, Comput.Phys.Commun. 140, 418 (2001)
[22] S. Frixione and B. R. Webber, JHEP 0206, 029 (2002)
[23] T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput.Phys.Commun. 178, 852 (2008)
[24] M. Cacciari, G. P. Salam, and G. Soyez, JHEP 0804, 063 (2008)
[25] M. Cacciari, G. P. Salam, and G. Soyez, Eur.Phys.J. C72, 1896 (2012)
[26] E. Conte, B. Fuks, and G. Serret, Comput.Phys.Commun. 184, 222 (2013)