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State-of-the-art generators for top physics

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Summary. — We describe the status and the availability of tools to simulate processes at hadron colliders where top quarks are present.

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1. – Introduction

The discovery and the study of several properties of the top quark are among the most significant achievements of the Tevatron era. At the LHC, the production rates for different top-quark production channels are much higher than at the Tevatron, and therefore it is foreseen that, in the next years, pinning down several properties of the top quark at an even higher accuracy will be possible. Moreover, production of top quarks will also become a background for some new physics searches, typically when tops are produced in association with jets.

On top of being relevant in a SM context, top physics is also expected to play an important role in elucidating the mechanism of electroweak symmetry breaking and in discovering new physics effects, the top quark being the only already discovered particle with mass of the same order of the electroweak symmetry-breaking scale. On a different ground, it is also interesting to notice that, in the recent past, one of the more statistically relevant discrepancy between data and SM predictions has been observed in the top sector (namely the charge asymmetry in $t\bar{t}$ pair production).

All the above arguments constitute a strong reason to provide the experimental community with as accurate predictions as possible for top-quark production and decay cross sections, and possibly with tools that allow the simulation of these processes realistically and with very high precision.

In the next sections the status of the art and recent progresses in these subjects will be summarized, with particular emphasis on the techniques used and the tools available for top physics at hadron colliders.

2. – Fixed-order computations

In order to obtain predictions where the theoretical uncertainty is small, the inclusion of higher order corrections is customary. Although a lot of progress has been done, a full NNLO computation of a process involving top quarks has not been completed yet, and nowadays the state of the art accuracy for signal and backgrounds processes relevant in top physics is NLO. Progress in the computation of NLO corrections has been very significant in the recent years, essentially due to:

- The development of methods to compute multileg one loop amplitudes efficiently.
- The implementation of subtraction methods in general purpose packages [1-3].

In particular, the computation of multileg one loop amplitudes (which has been for long time the technical bottleneck) has become possible either because of the introduction of new techniques, such as generalized unitarity with massive legs [4-8], or methods to perform the reduction of n-point one-loop integrals at the integrand level [9,10], or thanks to traditional methods based on tensor reduction. Some of these techniques have also been coded in public codes such as Cuttools [11] and Samurai [10], and afterwards also included in more automated packages, such as MadLoop, Helac-NLO and GoSam [12-14]. The existence of such packages, as well as of programs that automate the numerical integration of (IR regularized) multileg tree-level matrix elements via subtraction methods, allowed the computation of NLO corrections for processes with external massive particles, in association with other external light legs and/or with offshellness effects and decays taken into account, with various approximations.

Examples of very important processes computed at NLO recently are $t\bar{t}$ production at NLO with decays and offshellness effects [15-17], $t\bar{t}j$ [18,19], $t\bar{t}\gamma$ [20], $t\bar{t}Z$ [21], $t\bar{t}b\bar{b}$ [22,23] and $t\bar{t}jj$ [24]. Specific NLO corrections for single-top production have also been computed recently as well, as discussed in [25].

3. – Shower Monte Carlo's and matrix element corrections

In the phase space regions dominated by soft and collinear emissions, the result of a fixed-order computation is not reliable. A classic example would be the low-p_{T} spectrum of the $t\bar{t}$ system in inclusive $t\bar{t}$ production. As opposite to what one would obtain with fixed-order accuracy, it is known that at low p_{T} this distribution is damped because of Sudakov effects, due to multiple soft and collinear emissions. To describe these effects in a fully exclusive approach, the standard approach is to use parton shower (PS) algorithms implemented in Shower Monte Carlo event generators (SMC). Moreover, these multipurpose programs are important since they are the tool used by experimental collaborations to simulate events and study acceptances and detector effects, and in some cases also to discriminate between signals and backgrounds when multivariate analysis techniques are used. This is possible since a parton-shower algorithm allows not only to resum classes of (soft/collinear) Leading Logarithms (LL), but also to connect properly the high scattering process, typically simulated with $2 \to 1$ or $2 \to 2$ tree level accuracy, with the hadronization stage.

Nowadays, despite other tools are being developed, there are essentially 3 widely used programs: Herwig [26], Pythia 6 [27] and Sherpa [28]. Concerning these tools, it should be said that the C++ versions of Herwig and Pythia have now reached the level of maturity of their Fortran versions, and therefore in the future Herwig++ [29] and Pythia 8 [30], together with Sherpa, should become the default SMC programs to be used.

The other kinematical domain where neither SMC programs nor nowadays available fixed order NLO computations can provide a reliable description is the one where there are many hard jets in association with a $t\bar{t}$ pair. The goal here is to simulate these processes exploiting the capability of multileg LO matrix elements (ME) generators and parton shower algorithms of describing with good accuracy phase space regions dominated by hard or soft/collinear emissions, respectively. To achieve this task, a merging scheme is clearly needed, in order to avoid double counting and dead regions, and nowadays there are essentially 2 available and well tested methods: CKKW [31, 32] and the MLM-matching [33, 34].

Their practical implementation makes use of efficient matrix element generators [35-38] to generate events with many hard partons with LO accuracy, and the parton shower algorithms implemented in the aforementioned SMC programs to generate soft and collinear emissions. Eventually only those events that satisfy the matching prescription are kept in the final sample, which will have LO accuracy in the region of well separated jets, and LL accuracy in the soft/collinear regions.

4. – Parton showers with NLO accuracy

Another very important improvement of the aforementioned approaches has been the introduction of methods to consistently merge NLO computations and parton shower algorithms (NLO+PS). From a theoretical and a practical point of view, the advantages of these methods are the following:

- Inclusive observables (for example the top transverse momentum in $t\bar{t}$ production) are described with NLO accuracy.
- The 1st emission is described with the exact tree-level accuracy in the hard region, but at the same time collinear emissions are summed at the LL level. Therefore the hard tail of the 1st jet in $t\bar{t}$ production is simulated with the full $pp \to t\bar{t}j$ matrix element, whereas the low-p_T spectrum of the $t\bar{t}$ system exhibits Sudakov damping.

  The use of these programs allows to bring NLO accuracy at the level of event generation, with an obvious benefit for experimental studies: in fact some information needed for experimental analysis can be obtained only using SMC generators, and not from pure NLO computations.

Currently there are two available methods to reach this accuracy, named MC@NLO [39] and POWHEG [40, 41]; for the above reasons, these are nowadays the more accurate tools available to simulate signals and backgrounds, when the corresponding implementations are available. Despite being technically different, both have proven to work well, and, to a large extent, they agree for observables where they are supposed to. In few cases, differences were observed, and also understood.

The standard processes involving top quarks (top-pair production and single-top) have been available for some time [42-48], whereas, more recently, many other processes relevant for top physics were implemented successfully, namely $t\bar{t} + j/H/A/Z$ [49-53]. It is worth mentioning that this very fast progress has been possible since the used frameworks are modular and fully or partially automated [54, 55], so that different codes can be interfaced very efficiently.

Finally, a further step in improving the accuracy of these simulation tools was the introduction of the MENLOPS method (Matrix Element + NLO + Parton Shower), first proposed in [56] (where it was also applied to $t\bar{t}$ production in association with jets), and also developed in [57]. As the name suggests, this method allows to combine NLO computations matched to parton showers (so far when the POWHEG approach is used) with matrix-element corrections, the aim being to describe inclusive quantities with NLO accuracy, and at the same time to have exact tree-level accuracy in the multijet region, improving therefore the POWHEG and MC@NLO predictions.

5. – Outlook

The precision level incorporated in event generators have increased very quickly recently, and nowadays it is possible to simulate with NLO+PS tools essentially all processes relevant for top physics at the LHC, as far as SM signals are concerned. Some BSM processes have also been implemented, and even more sophisticated processes could be expected to be available in the future, because codes implementing state-of-the art techniques for the computation of multileg one-loop amplitudes can be interfaced together with automated implementation of the MC@NLO and the POWHEG methods.

It is clear that the same level of accuracy can be expected also for the simulation of backgrounds, that broadly speaking can be identified as processes with boson(s) in association with many hard jets. Especially for backgrounds, it is particularly important to improve well-established methods such as the CKKW and MLM-matching by including NLO corrections. The MENLOPS method represents a step in this direction, and ideas to go further have already appeared.

Other theoretical advances in this subject could be expected in the future, and thanks to the usage of these very precise tools, it will be possible to extract very accurate theoretical informations out of the analysis performed with the LHC data.

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