$\mathbf{t\bar{t}H/tH}$: Preliminary Recommendations and Future Plans

Stefan Guindon, Chris Neu, Stefano Pozzorini, Laura Reina

This document briefly summarizes the activity of the $t\bar{t}H/tH$ working group since October 2014, and focuses on a set of recommendations and a plan of proposed activities for 2015.

It is clear that the extraction of the $t\bar{t}H$ signal is very challenging and requires a fully differential simulation of both signal and several large multi-particle backgrounds. Sophisticated simulation and analysis environments make theory uncertainty estimates highly nontrivial. In particular, the discussion of particle-level Monte Carlo simulations based on NLO matching and multi-jet merging techniques, as well as the realistic assessment of all related theoretical uncertainties in the framework of experimental analyses, will play a key role in the activities of this working group. In this context, a much closer interaction between theory and experiment becomes crucial.

To coordinate the activity of both theorists and experimentalists we have organized a series of topical meetings over the last quarter of 2014 and early 2015 aimed at: i) discussing the status of (and plans for) $t\bar{t}H$ and tH experimental searches in various channels, with emphasis on the relevant Monte Carlo simulations, the assessment of related uncertainties, and the need of further improvements; ii) presenting the state-of-the art theory predictions, their current uncertainties and limitations, and possible improvements; iii) identifying and prioritizing all needed theoretical improvements.

In particular, in a series of six meetings with a total of ten experimental and six theoretical talks, we have discussed:

- Signal modeling in $t\bar{t}H$.
- Backgrounds and uncertainties in experimental $t\bar{t}H$, $H \to b\bar{b}$ searches.
- Theory perspectives on $t\bar{t}$+jets and $t\bar{t}$+HF (heavy flavour) production.
- Backgrounds and uncertainties in $t\bar{t}H$, $H \to \gamma\gamma$.
- Backgrounds and uncertainties in $t\bar{t}H$, $H \to$multileptons.
- $t\bar{t}H$ combination: systematics and correlations.

The first two meetings on single-top plus Higgs production will take place in January and February 2015:

- Signal modeling in tHq.
- Backgrounds and uncertainties in tHq.

This first series of meetings has attracted a lot of attention, which is reflected in the large number of subscriptions (more than a hundred) to the mailing list `lhc-higgs-xsbr-tth@cern`. The insights emerged from each meeting, as well as subsequent discussions and related information collected by the conveners, have been made publicly available in the form of extensive summaries on the working group TWiki page.

On the basis of the issues emerged during the meetings, in this document we would like to present a series of general recommendations and a preliminary plan that could guide the future work of this working group.

Overall Recommendations

1. A preliminary exercise should consist of benchmark comparisons among tools and methods, executed in cooperation by the proponents of these tools in the theory community. Specifically we plan to start with the $t\bar{t}H, H \to b\bar{b}$ signal and its $t\bar{t}b\bar{b}$ and $t\bar{t}$+jets backgrounds.

2. When tools are well cross-checked, it is important to focus not on specific generators, but on the best methods (matching and merging techniques, flavour number schemes, scale choices,...) to be used in order to address specific problems. The experiments should be strongly encouraged to exploit and compare all available tools that support state-of-the art methodology, seeking to identify the tool at highest precision, with smallest theoretical uncertainty that best represents the observed data.

3. All sources of theory systematics in NLO+PS simulations of signal and backgrounds should be assessed in detail (including parton shower effects, hadronization effects, etc.) in the environments of ATLAS/CMS analyses. In particular, based on quantitative studies, it is important to converge towards a satisfactory understanding of the uncertainties related to NLO matching and merging procedures and to arrive at a global and widely accepted prescription for the choice of the related scales (re-summation and merging scales) and for their variations. Understanding the intrinsic accuracy of the different methods and tools should be a central goal of this working group.

4. The working group should encourage and foster communication between theory and experiments while the previous goals are being pursued.

Specific preliminary Recommendations

1. **$\mathbf{t\bar{t}H}$ Signal**

   - NLO matching and merging for $t\bar{t}H$ production is available in `MadGraph5_aMC@NLO` as well as in `SHERPA+OpenLoops` (or `SHERPA` with other one-loop providers) and `PowHel` or `POWHEG BOX`: ATLAS and CMS need to use it with theorists' support.
   - It is desirable to include NLO QCD effects in top and Higgs decays.
   - Off-shell and interference effects should be investigated and included wherever relevant.
   - Electroweak NLO corrections are going to become available in the near future and are relevant in order to achieve 10% level precision in the boosted regime. They should be included also in the background simulations.

2. **$\mathbf{t\bar{t}}$+jets and $\mathbf{t\bar{t}}$+heavy-flavor backgrounds to $\mathbf{t\bar{t}H}$, $\mathbf{H \to b\bar{b}}$**

   - We recommend that the experiments acquire experience with the generation of $t\bar{t}$+jet samples using and comparing the various NLO multi-jet merging techniques and tools on the market, i.e. `FxFx` and `UNLOPS` with `MadGraph5_aMC@NLO` and `MEPS@NLO` with `SHERPA+OpenLoops`, possibly in strict collaboration with their main Authors. Such simulations are fully inclusive and can be used both for light- and heavy-flavour final states. Given the high technical complexity of $t\bar{t} + 2$ jets at NLO, in a first phase we recommend to restrict these investigations to $t\bar{t} + 0, 1$ jets merging.

- For an improved description of $t\bar{t}+b$-jets, we recommend that, using the above tools, the experiments acquire experience with NLO matched simulations of $t\bar{t}b\bar{b}$ in the Four-Flavour-Number Scheme (4FNS). Such simulations can be applied to the analysis of $t\bar{t}+b$ jet sub-samples that involve one or more b jets in addition to the two b jets that arise from top-quark decays.
- The $t\bar{t}+c$-jets process plays an important role in $t\bar{t}H$, $H\to b\bar{b}$ analyses at the LHC. These analyses would benefit from calculations of this process at NLO accuracy, which do not yet exist, as well as this process being the subject of NLO multi-jet merging techniques. Once available, these tools should be studied at the experiments as well.
- We encourage, theory and experiment, to present and document Monte Carlo studies in a transparent way, i.e. providing the full list of (default and user-defined) parameter choices and the considered variations.
- The understanding of theoretical uncertainties related to the various NLO matching and merging techniques (see general recommendations) plays an especially important role for $t\bar{t}$+jets and $t\bar{t}$+HF backgrounds. In this context, this working group should propose a coherent framework for quantitative studies and comparisons. The latter will provide the basis for official recommendations for uncertainty estimates.
- It is crucial to understand how to consistently provide $t\bar{t}$+jets results with $N_b=1$ and $N_b=2$ b-jets (see summary of this meeting for a more detailed discussion, in particular point (3)). The same will apply to $N_c=1$ and $N_c=2$ c jets. A systematic approach for the consistent combination of inclusive $t\bar{t}$+jets simulations and more exclusive $t\bar{t}$+HF simulations is also needed.
- The sizable impact, especially in the Higgs signal region, of $t\bar{t}b\bar{b}$ background contributions resulting from $g\to b\bar{b}$ parton-shower splittings and the related uncertainties deserve very careful investigations.

3. **Backgrounds to $\mathbf{t\bar{t}H}$, $\mathbf{H}\to\gamma\gamma$**

- This analysis involves background contributions from $t\bar{t}$, single-top and jets production in association with a variable number of photons, $N_\gamma=1,2$. We urge the experimental collaborations to quantify, using LO simulations, the importance of these backgrounds and to assess the relative benefits of precise Monte Carlo predictions with respect to a data-driven approach. This then motivates how much investment should be made in the theory community to the pursuit of NLO accuracy for the above-mentioned processes.
- Similarly as jets, also photons can be produced either at matrix-element level or through QED emissions in the parton shower (if the parton shower includes QED effects). In particular, final states with two photons can arise from matrix elements with $n=0,1,2$ photons in combination with $(2-n)$ photon emissions from the parton shower. This leads to possible double-counting problems that should be addressed with an approach analogous to multi-jet merging. We recommend to investigate the relevance of this issue in the context of $t\bar{t}+\gamma\gamma$.
- In addition to the need of merging photon emissions that originate from matrix elements and from the parton shower, one should consider also photon emissions that arise from the top-decay products. In principle one should thus consider an inclusive sample with $t\bar{t}+0,1,2$ photons, where photon emissions are consistently merged with the parton shower independently of top decays, and then one should allow for

additional photon emissions from top decays. In this respect we recommend to assess the importance (and the related theoretical uncertainty) of background contributions arising from photons that are emitted from top decays. This should be done by taking into account realistic photon isolation requirements (with respect to jets and leptons) as in the ATLAS and CMS analyses.

4. **Backgrounds to $\mathbf{t\bar{t}H}$, $\mathbf{H \to}$ multileptons**

   - Backgrounds from $t\bar{t}V$ and $VV + b\bar{b}$ $(V = W, Z)$ are difficult to constrain from data directly, and Monte-Carlo estimates and uncertainties play an important role. The General Recommendations listed above applies to these channels as well.
   - For $t\bar{t}V$+jets and VV+jets simulations the usage of the new tools based on NLO merging is recommended. To start with, up to one jet should be included at NLO. At the same time we urge the experiments to quantify the need of multi-jet simulations with more than one jet. In particular, the $t\bar{t}W$+jets background might require NLO precision up to two extra jets, and the need of such a challenging $2 \to 5$ NLO calculation should be supported by a realistic estimate of the needed $t\bar{t}W$+2 jet precision (and LO uncertainties) in the context of ATLAS/CMS analyses. Clear indications, from experimental side, on the kinematic observables that require accurate shape uncertainty estimates would also be very useful.
   - Spin correlations should always be included in any decay. This holds for all signal and background simulations.
   - In the case of the $t\bar{t}Z, Z \to \ell^+\ell^-$ background, the presence of a Z-veto in the experimental analyses calls for an off-shell treatment, i.e. for a full simulation of $t\bar{t}$+ dilepton production, including off-shell Z/γ contributions.
   - The quantitative importance of tV backgrounds with a single top quark in the ATLAS and CMS analyses should be assessed in more detail.

Future Plans

1. Complete the first round of topical meetings with the last two meetings, Jan. 26th and Feb. 2nd, on single-top modeling, both signal and background.

2. Consolidate the success of the first series of meetings with a series of recommendations that should trigger necessary activities.

3. Coordinate benchmark comparisons among various tools and methods based on standard setups (input parameters, variations, observables). A short meeting to discuss how to choose the best standard setups will be called soon and the result will be posted on the working group wiki page.

4. Support, coordinate and survey ATLAS/CMS Monte Carlo simulation and validation activities within this working group.

5. Address with ATLAS/CMS/theory possible new theory requirements for new Run2 ttH analyses (e.g., analyses exploiting boosted objects, or new techniques such as MEM-based analyses).

6. Organize a series of follow-up topical meetings to update on new results/work and catalyze various efforts to converge towards a coherent approach to the determination of theory systematics.

7. Priority should always be to facilitate the interaction and exchange of information between theorists and experimentalists. This will include inform about new/highest priorities and advertising new tools/studies within the working group community (using its mailing list and wiki page) even on a short notice.