$t\bar{t}H/tH$: Theory Overview

Laura Reina (FSU)

Theory conveners: S. Pozzorini, L. Reina

Experimental conveners: S. Guidon (ATLAS), C. Neu (CMS)

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Challenges, Strategy, and Goals for Run 2

- Challenges
  - ▷ describe large multi-particle backgrounds (automated NLO, NLO matching and merging with PS, ...)
  - ▷ understand and estimate theoretical uncertainty.
- Strategy and Goals
  - ▷ pinpoint most relevant processes:
    - $t\bar{t}H$
    - $t\bar{t} + b$ jets, $t\bar{t}+$ jets
    - $t\bar{t}W/Z$
    - $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$
    - tH
  - ▷ for each process:
    - compare available tools (NLO Monte Carlo), using a common setup
    - study the most relevant sources of theoretical uncertainty
    - agree on a recommendation to the experiments

    sequence of very delicate and process-dependent steps!

Overview of progress made since January meeting

↪ For a review of existing theory results see Stefano's talk at January meeting

- We have completed a first round of talks and started a new one
  - ▷ very good participation and focus (sign-up mailing list);
  - ▷ very productive to prioritize important issues and establish connections with ATLAS/CMS;
  - ▷ detailed minutes of each meeting available on line → basis for YR4.
- Emphasis has been on:
  - ▷ backgrounds and NLO matching+merging
  - ▷ tools (NLO Monte Carlo) comparison based on standard setups
  - ▷ calculation of missing effects (ex.: QCD+EW, signal-backgd interf.)
- Main progress:
  - ▷ signal → extensive testing of tools performed [↪ See Stefan's talk]
  - ▷ background → started tool comparison for NLO $t\bar{t} + b$ jets
  - ▷ QCD+EW corrections to $t\bar{t}H$ and $t\bar{t}V$ $(V = W, Z)$

    [automated in `MadGraph5_aMC@NLO`, `SHERPA+OpenLoops`, and `Recola`]
  - ▷ signal-background interference for $t\bar{t}b\bar{b}$ final state [Feger et al.]
  - ▷ $t\bar{t}H$ with off-shell top decays [Feger et al.]
  - ▷ completed NLO+PS tH implementation [`MadGraph5_aMC@NLO`]

Proposed comparison of $t\bar{t} + b$ jet NLO Monte Carlo simulations

[Full details at: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalTtbb]

- Comparing:
  - `SHERPA+OpenLoops` ($m_b > 0$)
  - `MadGraph5_aMC@NLO` ($m_b > 0$)
  - `PowHel` ($m_b = 0$)
- General setup recommendation: non trivial, not just a choice of parameters

  Ex.: b quarks can come from many sources:
  - matrix element
  - parton shower
  - top decays

  In order to test different NLO Monte Carlo, as well as to separate $t\bar{t} + b$ jets from inclusive $t\bar{t}+$ jets, a setup may be chosen to exclude some of these sources (e.g: switch off top decays, ...)
- Consistent heavy-flavour treatment: $N_f = 4$ vs $N_f = 5 \rightarrow \alpha_s \leftrightarrow$ PDF
- Consistent b-jet definition:
  - anti-k_T (R=0.4), full 4-momentum recombination
  - b jet = jet that involves one or more b quarks among the constituents
  - N_b= number of b jets with $p_T > 25$ GeV and $|\eta| < 2.5$

- Coherent treatment of theoretical uncertainty across different tools
  - $\mu_R =< E_T >_{\text{geom}}$, $\mu_F = \mu_Q = H_T/2$
  - scale variation (follow HXSWG recommendation)
  - PDF variation (follow HXSWG recommendation)
- Check benchmarks:
  - fixed order LO, NLO (no shower)
  - parton shower with no hadronization/UE/top decays
  - samples with different numbers of b jets
  - full Monte Carlo simulation
- Relevant runcards, Rivet analysis, results will be public
  - serve as benchmarks for validation of ATLAS and CMS simulations
- Recommendation (in case of small deviations): what is the best tool?
  "*accuracy*" is not "*precision*" ...
  - the most precise (theoretically) or the most tunable?
  - the one that better reproduces the data?
  - what if there are not enough data? like in our case ...
  - the one that does the best job in $t\bar{t}+$ jets? but, they are different processes ...
  - ...

  $\hookrightarrow$ Stefan's talk will offer several examples

$\hookrightarrow$ We are planning to have a similar exercise for $t\bar{t}+$ jets, $t\bar{t}+V$, and $t\bar{t}+\gamma(s)$

Off-shell $t\bar{t}H$ production and decay

[Denner, Feger, Scharf, arXiv:1412.5290, Denner and Feger, arXiv:1506.07448]

Full $2 \to 8$ process $pp \to t(bl^+\nu)\bar{t}(\bar{b}jj)H(b\bar{b})$ at LO

- include all possible channels with/without top and Higgs resonances
- include all QCD and EW contributions to matrix elements and interferences

matrix-element order	$O(\alpha_s^3\alpha)$	$O(\alpha_s^2\alpha^2)$	$O(\alpha_s\alpha^3)$	$O(\alpha^4)$
$t\bar{t}H(b\bar{b})$ signal			$\times$	$\times$
$t\bar{t}b\bar{b}$ background		$\times$	$\times$	$\times$
full process ($l^+\nu + 2j + 4b$)	$\times$	$\times$	$\times$	$\times$

- Results for 13 TeV LHC:
  - $\to$ negligible $t\bar{t}H$ signal-background interference
  - $\to$ significant -8% interference between QCD and EW contributions to $t\bar{t}b\bar{b}$ background (from W exchange in t-channel)
  - $\to$ significant +11% enhancement in $t\bar{t}b\bar{b}$ background from diagrams without top resonances

Full $2 \to 7$ process $pp \to t(be^+\nu_e)\bar{t}(\bar{b}\mu^-\nu_\mu)H$ at NLO in QCD

- include all non-resonant effects, off-shell effects, and interferences
- effects of only 1% on total cross section

NLO QCD predictions for $pp \to tHj$ at 13 TeV

[Demartin, Maltoni, Mawatari, Zaro, arXiv:1504.00611]

Ingredient of the calculation

- NLO and MC@NLO predictions
- t-channel and s-channel contributions
- comparison of 4F and 5F schemes
- uncertainties from scale variations, PDFs, α_s, m_t, m_b

NLO cross sections and uncertainties at 13 TeV

- low scale $\mu = (m_H + m_t)/4$ in order to obtain satisfactory 5F-4F agreement (within 5% at NLO)
- NLO corrections reduce scale dependence from 25% (4F scheme) to 5% (both schemes)

NLO QCD+EW corrections for $t\bar{t} + H/Z/W$ production

[Frixione, Hirschi, Pagani,Shao, Zaro, arXiv:1504.03446]

$\sqrt{s} = 13$ TeV	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W^+$	$t\bar{t}W^-$
NLO scale uncertainty	[+7,-11]%	[+13,-16]%	[+14,-14]%	[+15,-14]%
LO QCD-EW interference	+1.2%	0%	0%	0%
NLO EW corrections	-1.2%	-3.8%	-7.7%	-6.7%

- inclusive cross section: NLO EW corrections $\ll$ NLO QCD uncertainty
- Boosted regime: $p_t, p_{\bar{t}}, p_H \geq 200$ GeV $\Rightarrow$ 8 (11-20)% negative corrections for $t\bar{t}H$ ($t\bar{t}V$)

Plan towards YR4

- Report results of tool comparison (see $t\bar{t}+b$-jet discussion) for
  - $t\bar{t}+b$ jets
  - $t\bar{t}+$ jets
  - $t\bar{t}+H/Z/W$
  - $t\bar{t}+\gamma$(s)

  coordinating with experimental benchmark validation.

  Emphasis will be put on coherent definition of theoretical uncertainties.

  $\hookrightarrow$ Some of these studies will be coordinated with MC studies within the Les Houches 2015 Workshop.

- Review of theoretical results with focus on more recent ones, such as:
  - NLO QCD predictions for $pp \to tH + j$ at 13 TeV
    [Demartin et al. $\to$ `MadGraph5_aMC@NLO`]
  - Off-shell $t\bar{t}H(b\bar{b})$ production and decay: interference effects between signal and background (LO) [Denner et al.]
  - Off-shell $t\bar{t}H$ production with top leptonic decays at NLO in QCD [Denner et al.]
  - NLO QCD+EW corrections to $t\bar{t}+H/Z/W$ production
    [Frixione et al. $\to$ `MadGraph5_aMC@NLO`]