$t\bar{t}H$ signal and background with PowHel

M.V. Garzelli, A. Kardos, Z. Trócsányi

II Institute for Theoretical Physics, University of Hamburg, Germany
MTA-DE Particle Physics Research Group, Debrecen, Hungary

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PowHel = HELAC-NLO + POWHEG-BOX

Interface between different *public* event generators:

- All LO and NLO matrix-elements: HELAC-NLO
  `http://helac-phegas.web.cern.ch/helac-phegas/`
- Subtraction of IR divergences and matching NLO + PS: POWHEG-BOX
  `http://powhegbox.mib.infn.it/`
- Parton and photon shower emissions: SMC codes (PYTHIA-6, -8, HERWIG)
- Hadronization and hadron decay: SMC codes (PYTHIA-6, -8, HERWIG)

OUTPUT:
Les Houches event files
and predictions at both parton and hadron level
with NLO QCD + Parton Shower accuracy
for p-p and p-$\bar{p}$ processes

PowHel + SMC: processes studied so far at LHC/Tevatron

- pp and $p\bar{p} \to t\bar{t}$ [arXiv:1405.5859]
- pp and $p\bar{p} \to t\bar{t}j$ [arXiv:1101.2672]
- $pp \to t\bar{t}H/t\bar{t}A$ [arXiv:1108.0387], [arXiv:1201.3084]
- $pp \to t\bar{t}Z$ [arXiv:1111.1444], [arXiv:1208.2665]
- $pp \to t\bar{t}W^+$, $t\bar{t}W^-$ [arXiv:1208.2665]
- $pp \to t\bar{t}b\bar{b}$ [arXiv:1303.6291], [arXiv:1307.1347], [arXiv:1408.0266]
- pp and $p\bar{p} \to (t\bar{t} \to W^+W^-b\bar{b}) \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ [arXiv:1405.5859]
- $pp \to t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$ [arXiv:1406.2324], [arXiv:1408.0278]

All these processes involve the production of a $t\bar{t}$ pair.

$t\bar{t}H$ signal

* increasing interest with increasing LHC energy:

$$\sigma_{NLO}\,(8\text{ TeV}) = 127.7\text{ fb}\ {}^{+3.8\%}_{-9.3\%}\ {}^{+8.1\%}_{-8.1\%}$$
$$\sigma_{NLO}\,(14\text{ TeV}) = 604.3\text{ fb}\ {}^{+5.9\%}_{-9.3\%}\ {}^{+8.9\%}_{-8.9\%}$$

($m_H = 125.5$ GeV, HXSWG predictions)

* direct access to top Yukawa coupling

* experimentally exploited channels:

$$H \to b\bar{b},\ H \to \ell^+\ell^-\ (\text{in particular } \tau^+\tau^-),\ H \to \gamma\gamma.$$

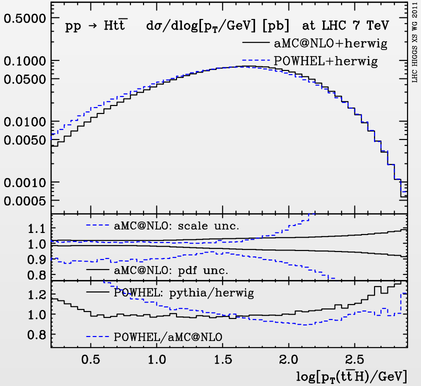
* main difficult issues (both for experiments and for theory):
  - background estimates with high precision, in particular
    - $t\bar{t}$ + Heavy Flavour jets ($b\bar{b}$, $c\bar{c}$, b, c)
    - $t\bar{t}$ + light jets (1,2,3.....)
  - determination of the signal uncertainties and of their correlations with the uncertainties in other H production channels, in a combined analysis of the four (updated to five, including $b\bar{b}H$) main H production channels.

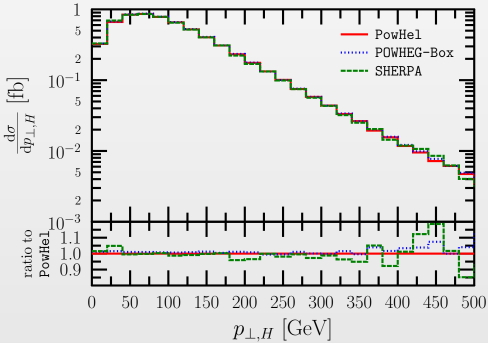
$t\bar{t}H$ signal: PowHel predictions

$*$ PowHel predictions at NLO QCD + PS accuracy already in [arXiv:1108.0387].

$*$ Comparison with other predictions (aMC@NLO, POWHEGBOX, SHERPA) with the same accuracy:

Frederix, Garzelli, Kardos, Papadopoulos, Trócsányi in [arXiv:1201.3084],
Garzelli, Hartanto, Jager, Kardos, Reina, Wackeroth in [arXiv:1405.1067].





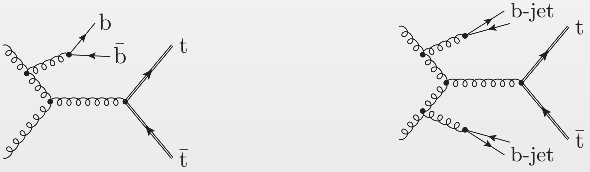
$t\bar{t}H$ backgrounds: the $t\bar{t}b\bar{b}$ case

$*$ Big experimental uncertainties ($\sim 50\%$), difficulties in finding a signal-free control region, need for theoretical predictions at NLO QCD (+ PS) accuracy.

$*$ Two theoretical calculations with NLO QCD + PS accuracy:

- $t\bar{t}b\bar{b}$ with $m_b = 0$ by PowHel [Kardos, Trócsányi arXiv:1303.5912]
- $t\bar{t}b\bar{b}$ with $m_b = m_b^{pole}$ by OpenLoops + SHERPA [Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert arXiv:1309.5912]

$*$ Difference among them: "degree" of inclusion of single collinear $g \to b\bar{b}$ splitting and double collinear $g \to b\bar{b}$ splitting.



In PowHel "small" technical cuts $p_{\perp,b} > 2$ GeV and $m_{b\bar{b}} > 2$ GeV on the b's in the "first" splitting, whereas OpenLoops + SHERPA uses finite b-mass $\sim$ 4.75 GeV, corresponding to $m_{b\bar{b}} > 9.5$ GeV, no inferior limit on $p_{\perp,b}$.

Examples of still unsolved questions

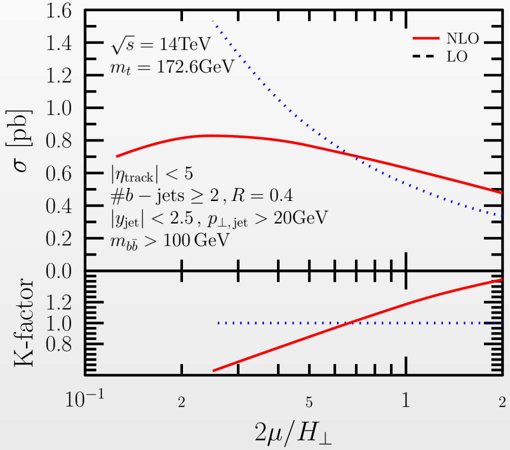
$*$ In the 5 FNS: how to solve the mismatch arising from matching a parton level calculation with $m_b = 0$ with SMC codes which have a fixed and finite m_b (always kept the same during parton shower evolution and hadronization) ? What's the related uncertainty ?

$*$ In the 4 FNS: what's the meaning of using just b-pole mass in the hard scattering computation ? Slowness in the convergence of the perturbative series ? Effects of higher order corrections can be considerable......

$*$ In the Parton Shower: what's the role of $g \to b\bar{b}$ splittings (loosely constrained by experimental data) and the interplay between b jets generated by these splittings and those from the hard scattering ?

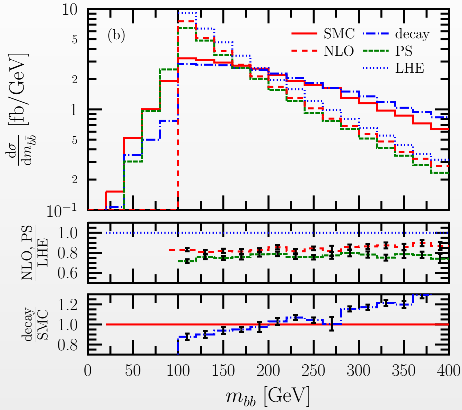
Other issues: choice of the μ_R and μ_F scales

$t\bar{t}b\bar{b}$ is a multiscale process: Q, m_t, m_b.



Kinematics better described in a dynamical scale framework.

$t\bar{t}b\bar{b}$: comparison NLO/LHE/decay/PS/SMC



∗ Cuts at NLO/LHE level: at least 2 "primary" b-jets with $p_\perp > 20$ GeV, $\eta < 2.5$ and $m_{bb} > 100$ GeV.

∗ PS effects: shape softening, i.e. the m_{bb} region below 100 GeV is populated, while the high energy tail is slightly depopulated.

∗ Top-decay effects: shape deformation, i.e. both the region below 100 GeV and the high energy tail are populated.

∗ Shape of distri at the hadron level (SMC) are determined by both PS and top-decay effects.

$t\bar{t}b\bar{b}$: example of analysis at the hadron level

$\ast$ Recent experimental study of the $t\bar{t}jj/t\bar{t}b\bar{b}$ cross-section ratio at $\sqrt{s} = 8$ TeV, $L = 19.6\ fb^{-1}$ in CMS-PAS-TOP-13-010.

$\ast$ NLO predictions for both $t\bar{t}jj$, $t\bar{t}b\bar{b}$ and their ratio by HELAC-NLO [Bevilacqua, Worek arXiv:1403.2046].

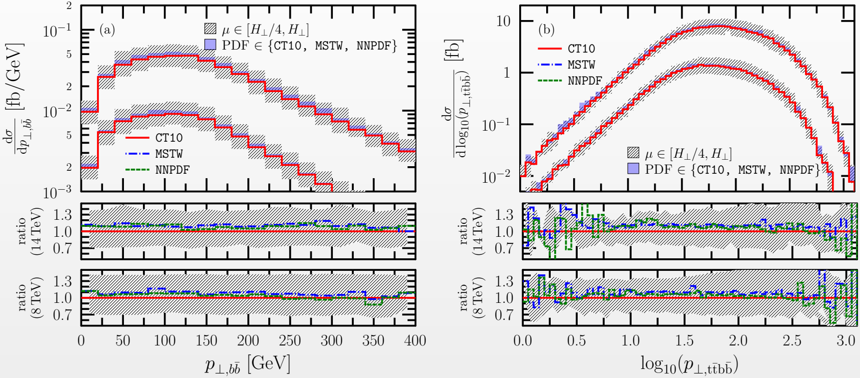
$\ast$ NLO QCD + PS predictions for $t\bar{t}b\bar{b}$ by PowHel + PYTHIA [Garzelli, Kardos, Trócsányi arXiv:1408.0266].

$p_{\perp,j} > 40$ GeV	(e,e)	$(\mu,\ \mu)$	$(e,\ \mu)$	Total
predictions in exp. analysis (LO MadGraph5+PYTHIA)	4.0 ± 0.4	5.9 ± 0.5	13.3 ± 0.7	23.3 ± 1.5
predictions by PowHel+PYTHIA	$6.82\ ^{+2.78}_{-2.00}$	$6.76\ ^{+2.75}_{-2.02}$	$19.54\ ^{+8.31}_{-5.56}$	$33.12^{+13.84}_{-9.52}$

$p_{\perp,j} > 20$ GeV	(e,e)	$(\mu,\ \mu)$	$(e,\ \mu)$	Total
predictions in exp. analysis (LO MadGraph5+PYTHIA)	18.1 ± 0.8	26.8 ± 1	60.9 ± 1.5	105
predictions by PowHel+PYTHIA	$30.32\ ^{+13.62}_{-9.35}$	$29.36\ ^{+11.25}_{-8.19}$	$87.84\ ^{+38.60}_{-25.59}$	$147.53\ ^{+63.46}_{-43.14}$

$t\bar{t}b\bar{b}$ differential distributions at the hadron level

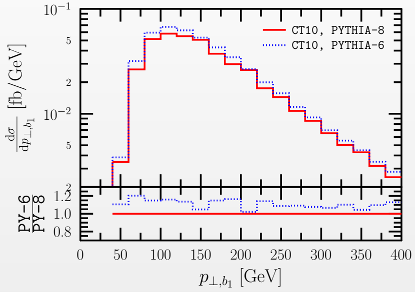
cuts inspired to CMS-PAS-TOP-2013

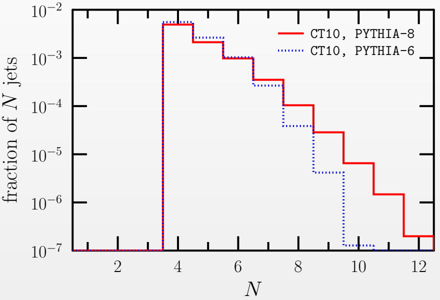


∗ Distributions at $\sqrt{s} = 8$ TeV with tails slightly steeper than those at 14 TeV.

∗ Using $\mu_R = \mu_F = \mu_0 = H_T/2$ scale variation bands are quite uniform within distributions and with $\sqrt{s}$ variations.

$t\bar{t}b\bar{b}$ prediction sensitivity to different SMC codes

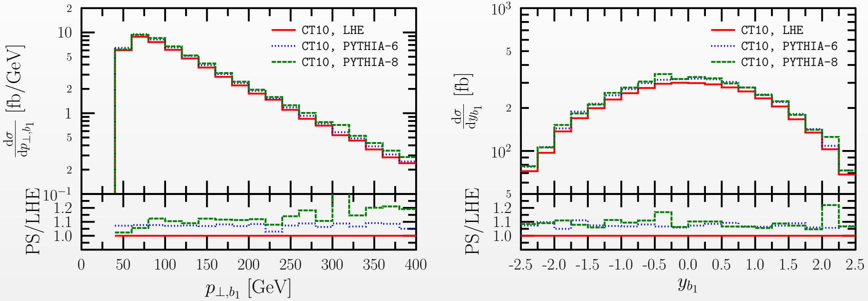




* At the hadron level, PYTHIA-8 Monash 2013 tune gives predictions globally slightly smaller (1 - 10 % depending from process and cuts) than PYTHIA-6 Perugia 2011 tune.

* Differences in jet distributions, related to the production of more b-jets from $g \to b\bar{b}$ splittings in PYTHIA-8.

$t\bar{t}b\bar{b}$ prediction sensitivity to different PS codes

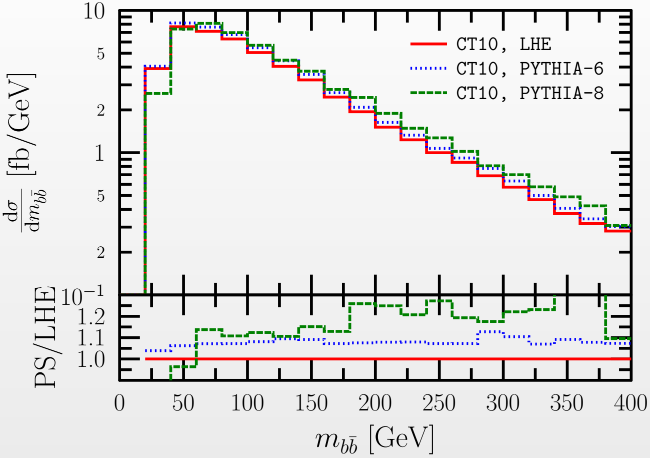


$*$ Cuts: top stable, at least 2 well-separated (DR=0.5) b jets (anti-kt, R=0.5) with $p_T > 40 GeV$ and $\eta < 2.5$.

$*$ σ_{PS} is a few percent larger than σ_{LHE}.

$*$ LHE vs. PS level: the hardest *b*-jet at LHEF level remains mostly the hardest even after PS.

$t\bar{t}b\bar{b}$ prediction sensitivity to different PS codes



∗ LHE vs. PS level: differences in shapes, related to the production of more b-jets from $g \to b\bar{b}$ splittings in PYTHIA-8 with respect to PYTHIA-6.

∗ σ_{PS} is a few percent larger than σ_{LHE}.

$t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$

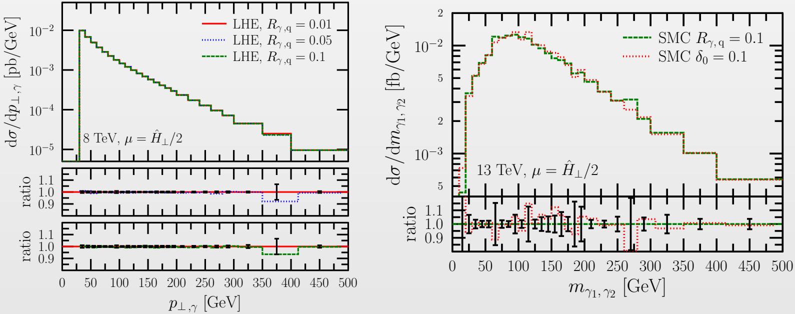
Kardos, Trócsányi [arXiv:1406.2324], [arXiv:1408.0278]

$*$ irreducible background for $t\bar{t}H$ with $H \to \gamma\gamma$

$*$ quark-photon collinear singularities regularized by a technical cut on the real emission phase-space: possible because fragmentation contribution becomes negligible in a cone with radius $R_{\gamma,q} \to 0$.

$*$ LHE events generated with technical cuts on the basis of either fixed cone isolation or Frixione isolation, with $R_{\gamma,q}$ or δ_0 small enough that the results after SMC do not depend on these parameters and on the type of "technical" isolation.

$*$ Can be showered and used to produce results at hadron level using experimental cone isolation, without need of including non-perturbative fragmentation contribution.



Conclusions

$*$ Set of LHE events by `PowHel` for all processes studied so far available for download from `http://grid.kfki.hu/twiki/bin/view/DbTheory/`

$*$ Further sets (for different energies/parameters) can be made available upon request.

$*$ Events for different μ_R and μ_F scale/PDF choice can be obtained by reweighting (no need for a full generation from scratch).

$*$ Use of dynamical scales is recommended not only for complex backgrounds but even for the $t\bar{t}H$ signal in order to study boosted top configurations.

$*$ $t\bar{t}b\bar{b}$: effects of top decays is significant on distributions at hadron level, 5-flavour vs. 4-flavour scheme comparison to be done.

$*$ $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$: events available on top of which physical cuts involving either Frixione isolation (theoretical) or just cone isolation (closer to the experiment) are applicable. Generalization to $t\bar{t}$ + nγ.