$t\bar{t} + X$ hadroproduction at NLO with decay and evolution to the hadron level

M.V. Garzelli, A. Kardos, C.G. Papadopoulos, Z. Trocsanyi

University of Nova Gorica - University of Debrecen - NCSR Demokritos Athens
e-mail: `garzelli@ugr.es`

2nd LHCPhenonet Annual Meeting,
Lumley Castle, Durham, March 20th, 2012

Hard scattering matched to Parton Shower evolution

$*$ Hard scattering matrix elements are suitable for describing large angle and high energy emissions.

$*$ However, matrix elements become singular in phase space points corresponding to soft and/or collinear emission configurations, leading to infinite cross-sections.

$*$ Parton shower approaches resum leading log terms corresponding to soft and/or collinear emissions at all orders in perturbation theory.

$*$ The best is matching the two complementary approaches, to get the optimum from each of them.

$*$ The matching procedure should solve two problems: double counting and dead regions, and allows for a smooth transition between different regimes.

$*$ LO matching procedures: CKKW (`SHERPA`), MLM (`HELAC`, `ALPGEN`, `MadGraph`), Lonnblad prescription in dipole emission (`ARIADNE`).....

$*$ NLO matching procedures: MC@NLO, POWHEG, Catani-Seymour splitting kernels....

PowHel+SMC: ingredients of our numerical approach

- HELAC-NLO: to compute all Matrix Elements required as input by POWHEG-BOX.
- POWHEG-BOX: to generate events at "NLO QCD matched to Parton Shower" accuracy.
- Shower Monte Carlo code: PYTHIA or HERWIG: to generate Parton Shower emissions (except the first one, already computed by POWHEG-BOX in a SMC independent way), elementary particle decays (t, W, Z, H....), hadronization, hadron decay.

HELAC-NLO

* HELAC-NLO is a set of public automatic event generators (HELAC1loop and HELAC-Dipoles) for the computation of pp, $p\bar{p}$, e^+e^- scattering amplitudes in the SM, including NLO QCD virtual and real corrections, their integration and the subsequent unweighted event generation.

* As a byproduct it can also be used to generate tree-level scattering amplitudes and cross-sections.

http://helac-phegas.web.cern.ch/helac-phegas/

[G. Bevilacqua, M. Czakon, M.V.G., A. van Hameren, A. Kardos, C.G. Papadopoulos, R. Pittau, M. Worek, arXiv:1110.1499 [hep-ph]]

POWHEG-BOX

∗ POWHEG-BOX is a public numerical computer framework for matching NLO QCD calculations to SMC, on the basis of the POWHEG approach.

∗ The POWHEG matching approach was designed since the beginning in order to be independent from the details of the specific SMC.

http://powhegbox.mib.infn.it/

[P. Nason, JHEP 0411 (2004) 040, hep-ph/0409146]
[S. Frixione, P. Nason and C. Oleari, JHEP 0711 (2007) 070, arXiv:0709.2092]
[S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 1006 (2010) 043, arXiv:1002.2581]

PowHel: HELAC-NLO **interfaced to** POWHEG-BOX

* All matrix elements used in our calculations and required as input by POWHEG-BOX are generated by HELAC-NLO codes interfaced to POWHEG-BOX.

* IR divergence subtraction is always performed by POWHEG-BOX, on the basis of the FKS subtraction scheme.

* Phase-space kinematics and integration variables are specified by the user (process-dependent).

* Phase-space integration is always performed by POWHEG-BOX.

* So far, the interface is process-dependent.....

* the output is a file of events at the first radiation emission level in the Les Houches format (LHEF).

Shower Monte Carlo generators

∗ POWHEG-BOX has already been interfaced to the fortran version of PYTHIA and HERWIG.

∗ All radiation emissions (except the first one, already computed by POWHEG-BOX) are computed by the chosen SMC.

∗ Both ISR and FSR can be included (or switched off....).

∗ Elementary particle decays according to the chosen SMC (B.R. in different channels can differ in different SMCs....).

∗ Hadronization and hadron decay through phenomenological models (parameters in the SMC, tuned to data).

∗ MPI effects: phenomenological models, switched off in our simulations.

How to compare the effect of different SMC ?

$*$ PYTHIA: Q or p_t ordered shower / HERWIG: angular ordered shower

$*$ PYTHIA: string hadronization model / HERWIG: preconfinement (on the basis of color) and cluster hadronization model

$*$ particle masses and total widths: often differ in the two codes

$*$ B.R. for particle and hadron decays: often differ in the two codes

$*$ Naive comparisons: use the two SMC in their "default configuration" and look at the results. The differences give insights concerning a conservative estimate of the uncertainty associated with changing the SMC approach (by the way: estimate the accuracy of a PS approach is not an easy task....).

$*$ Slightly more refined comparisons: reconfigure some of the parameters (typically masses, widths, B.R.s, etc....) in the two SMC, tune them to the same values in both (and, in case of heavy particles, accordingly to the parton level hard-scattering calculation).

Assumptions in the SMC setup

* π^0 assumed as stable (they can be easily reconstructed from photons produced by their decay, from the experimental point of view).

* μ stability (this is PYTHIA default....we forced it also in HERWIG).

* τ stability (this can be forced both in PYTHIA and in HERWIG): we adopt this assumption only in some cases.....(e.g. LHEF with on-shell τ's in the final states). From the experimental point of view efforts are being made to reconstruct τ's....

* B-hadron stability (this can be forced both in PYTHIA and in HERWIG): we did not adopt this assumption, if we are interested in the study of B-hadron decay products (e.g. missing energy, leptons.....).

* Actually (both in the simulation and in the experiment) all B-hadrons decay in lightest flavour hadrons, and the corresponding light jets are tracked in the detectors. In the experiment, B-hadrons are reconstructed as displaced vertices (with respect to the primary interaction vertex) with tracks pointing towards them. In the theoretical simulation framework, the information included in MCTRUTH can be used to understand if a light jet is a residual of a B-hadron decay.

Predictions at different levels

By means of PowHel+SMC, we can produce predictions at different levels:

∗ exact NLO level: results of an exact QCD NLO computation (PowHel also allows for this kind of computations.....).

∗ LHEF level (to be compared to the exact NLO level): not too “physical”, but SMC independent (this is a typical feature of POWHEG)....

∗ Decay level: we just include heavy particle decay (t, W, Z, H), computed by the SMC, turning off any ISR and FSR effect (except first radiation emission, already present in the LHEF).

∗ Shower level: results after decay and showering (but before hadronization).

∗ Shower + Hadronization + Hadron decay level: final results, the closest to the experimental data.

Top decay

$*$ In the $t\bar{t}Z$ and $t\bar{t}H$ simulations shown in the following top quarks are produced on shell, and their decays are simulated by the SMC in the narrow width approximation, neglecting spin correlations.

$*$ Actually `PowHel` is a flexible framework: in its last version elementary top decays can be generated by independent pieces of codes, allowing for more control of this phase (e.g. by linking the `Decayer` code, see Adam's talk). The effect of off-shell top quarks can be treated as well, by describing their propagators in the complex mass scheme (propagator denominator $= p^2 - m_t^2 + i m_t \Gamma_t$).

Processes involving t-quarks simulated by PowHel+SMC

* $t\bar{t}j$ @ both Tevatron and LHC
* $t\bar{t}H$, $t\bar{t}A$ @ LHC in this talk
* $t\bar{t}Z$ @ LHC in this talk
* $t\bar{t} \to W^+W^-b\bar{b}$ vs. $W^+W^-b\bar{b}$ (including off-shell tops) @ LHC (see Adam's talk)

[A. Kardos, C.G. Papadopoulos, Z. Trocsanyi arXiv:1101.2672]
[M.V.G., A. Kardos, C.G. Papadopoulos, Z. Trocsanyi arXiv:1108.0387]
[M.V.G., A. Kardos, C.G. Papadopoulos, Z. Trocsanyi arXiv:1111.1444]
[M.V.G., A. Kardos, Z. Trocsanyi arXiv:1111.1446]
[R. Frederix, M.V.G., A. Kardos, C.G. Papadopoulos, Z. Trocsanyi in arXiv:1201.3084]

$t\bar{t}Z$ hadroproduction @ LHC

Parameters entering the numerical simulation: $\sqrt{s} = 7\,\mathrm{TeV}$ or $\sqrt{s} = 14\,\mathrm{TeV}$, `CTEQ6.6M` PDF set from `LHAPDF`, with a 2-loop running α_s, 5 light flavours and $\Lambda_5^{\overline{\mathrm{MS}}} = 226\,\mathrm{MeV}$, $m_t = 172.9\,\mathrm{GeV}$, $m_Z = 91.1876\,\mathrm{GeV}$, $G_F = 1.16639 \cdot 10^{-5}\,\mathrm{GeV}^{-2}$, $\mu_R = \mu_F = \mu_0 = m_t + m_Z/2$.

Jet reconstruction: anti-kt with R=0.4

Inclusive cross-section $\sigma = 138.7 \pm 0.01 fb$ ($\sqrt{s} = 7$ TeV)

$t\bar{t}Z$, inclusive: LHEF level vs NLO level

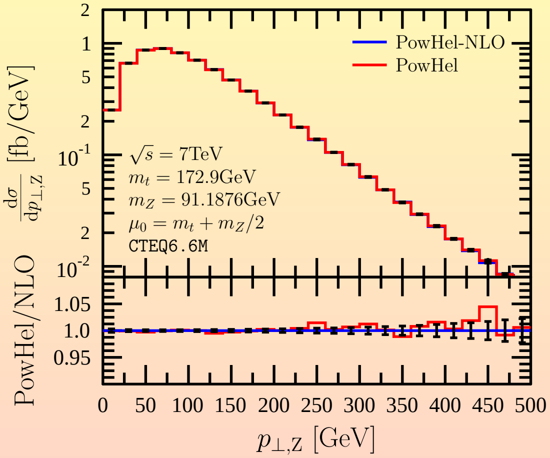

Figure: Inclusive transverse momentum of the Z boson at NLO and LHEF level. The lower panels show the ratio of the predictions with combined statistical uncertainties

$t\bar{t}Z$, inclusive: LHEF level vs NLO level

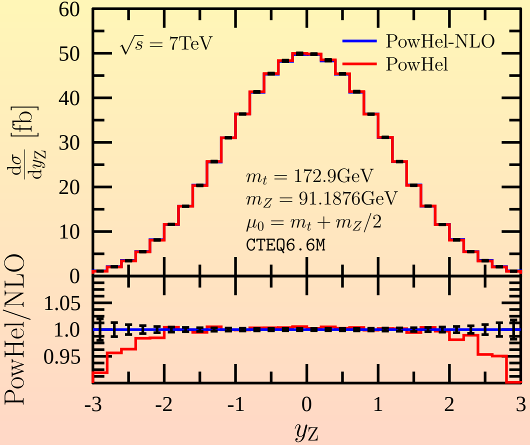

Figure: Inclusive rapidity of the Z boson at NLO and LHEF level. The lower panels show the ratio of the predictions with combined statistical uncertainties

$t\bar{t}Z$, inclusive: shower+had level vs. decay level

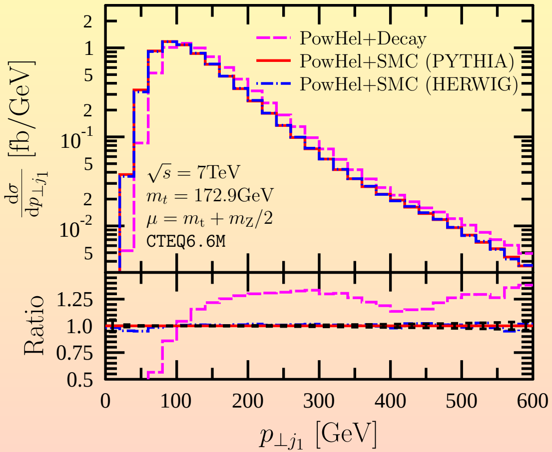

Figure: Inclusive transverse momentum distribution of the hardest jet after decay (simulated by means of PYTHIA) and after full SMC, by considering both PYTHIA and HERWIG . The lower panels show the ratio of all predictions to PowHel+SMC using PYTHIA.

$t\bar{t}Z$, inclusive: shower+had level vs. decay level

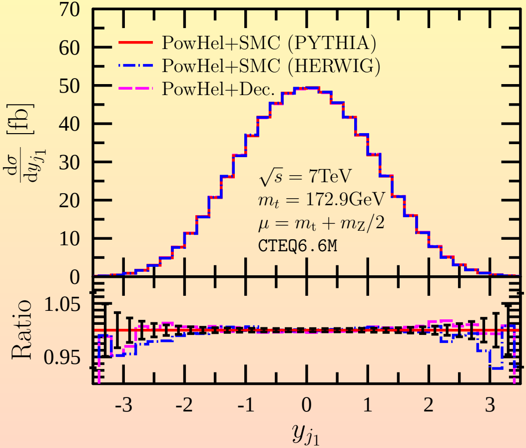

Figure: Inclusive rapidity (right) distribution of the hardest jet after decay (simulated by means of PYTHIA) and after full SMC, by considering both PYTHIA and HERWIG . The lower panels show the ratio of all predictions to PowHel+SMC using PYTHIA.

Example of signal over background study: ttz vs. ttj

$\sigma(t\bar{t}Z)$= 138.7 $\pm$ 0.01 fb ($\sqrt{s} = 7\,TeV$)

$\sigma(t\bar{t}Z)$= 982.49 $\pm$ 0.10 fb ($\sqrt{s} = 14\,TeV$)

$\sigma(t\bar{t}j)$= 1056.46 $\pm$ 0.33 pb ($\sqrt{s} = 14\,TeV$)

The background overwhelms the signal by 3 order of magnitudes!

$t\bar{t}z$ vs. $t\bar{t}j$: cuts aimed at favouring the $t\bar{t}Z \to \not{p}_\perp b\bar{b}$ + 4 jet channel:

1) we reconstruct at least six jets with rapidity $|y| < 2.5$,
2) of these we require at least one b-jet and one $\bar{b}$-jet,
3) for b-jets $p_\perp^b > 20\,\mathrm{GeV}$,
4) for other jets $p_\perp^{\mathrm{non}-b} > 30\,\mathrm{GeV}$,
5) at least 3 jets (b or non-b) with $p_\perp^j > 50\,\mathrm{GeV}$,
6) $\Delta R(j,j) > 0.4$, where j denotes any (b or non-b) jet and ΔR is defined as $\sqrt{\Delta\phi^2 + \Delta y^2}$,
7 – 8) $\Delta\phi(\not{p}_\perp, p_{\perp,j}) > 100^\circ$, with $p_{\perp,j}$ meaning either $(p_\perp(\hat{b}_1) + p_\perp(\hat{\bar{b}}_2))$ (cut 7), or $(p_\perp(\hat{j}_1) + p_\perp(\hat{j}_2) + p_\perp(\hat{j}_3) + p_\perp(\hat{j}_4))$ (cut 8),
where $\hat{b}_1$, $\hat{\bar{b}}_2$ and $\hat{j}_1$, $\hat{j}_2$, $\hat{j}_3$, $\hat{j}_4$ are the jets that allow for the best $\mathrm{t} \to \mathrm{b}\mathrm{W}^+ \to bjj$ and $\bar{\mathrm{t}} \to \bar{\mathrm{b}}W^- \to \bar{b}jj$ invariant mass simultaneous reconstruction, by minimizing the

$$\chi^2(b_1j_1j_2;\bar{b}_2j_3j_4) = \frac{(m_{j_1j_2}-m_W)^2}{\sigma_W^2} + \frac{(m_{j_3j_4}-m_W)^2}{\sigma_W^2} + \frac{(m_{b_1j_1j_2}-m_W)^2}{\sigma_\mathrm{t}^2} + \frac{(m_{\bar{b}_2j_3j_4}-m_W)^2}{\sigma_\mathrm{t}^2},$$

computed by considering all possible j_kj_l, $b_ij_kj_l$ and $\bar{b}_ij_kj_l$ combinations. The $W \to jj$ and $\mathrm{t} \to bjj$ invariant mass resolutions were set to $\sigma_W = 7.8\,\mathrm{GeV}$ and $\sigma_t = 13.4\,\mathrm{GeV}$, respectively.

9) missing transverse momentum $\not{p}_\perp(\text{due to all } \nu\text{'s}) > 5\,\mathrm{GeV}^{1/2}\sqrt{\sum_j p_\perp^j}$ (of all jets, b or non-b),
10) $\chi^2_{\min} < 3$, where $\chi^2_{\min}$ is the minimum of the χ^2 above.

$t\bar{t}$-quark invariant mass: ttz vs. ttj

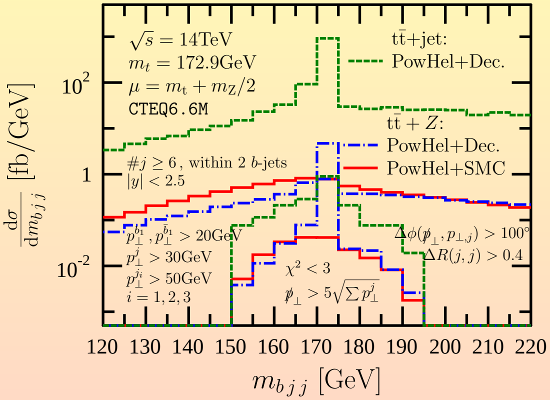

Figure: Invariant mass distribution of the t-quark reconstructed from the decay products at both decay (blue dash-dotted lines) and full SMC (red solid lines) levels, for the $t\bar{t}Z$ signal and, at the decay level, for one background ($t\bar{t}$+jet) (green dashed lines) after selection cuts (1–8) (wider distributions in abscissa values) and after selection cuts (1–10) (narrower distributions).

$\not{p}_\perp$: ttz vs. ttj

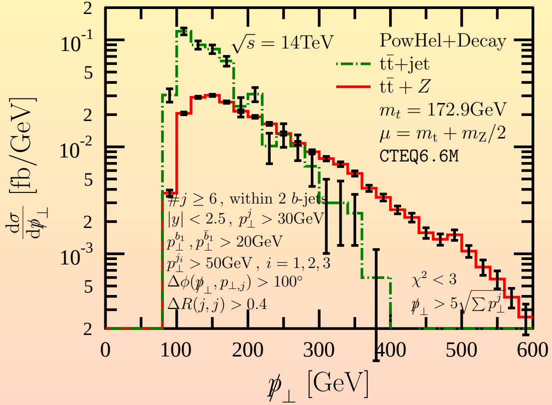

Figure: Distribution of the missing transverse momentum after decay, under physical cuts (1–10) applied to the signal ($t\bar{t}Z$, solid line) and to one background ($t\bar{t}$+jet, dash-dotted line).

$\sigma^{cut}(t\bar{t}Z) = 4.83 \pm 0.04$ fb, $\sigma^{cut}(t\bar{t}j) = 9.86 \pm 1.05$ fb ($\sqrt{s} = 14\,TeV$)

Further refinements

* b-tagging efficiencies
* other backgrounds
* variation of the R parameter in jet reconstruction
* variation of jet reconstruction algorithm (small effect)

$t\bar{t}H$ and $t\bar{t}A$: comparisons between PowHel and aMC@NLO

in collaboration with R. Frederix, on behalf of the aMC@NLO group.

Parameters and Assumptions:

* For both scenarios the Higgs boson mass was set to $M_H = 120$ GeV and standard Yukawa couplings were assumed. The top mass was assumed to be $M_t = 172.5$ GeV. A dynamical scale, defined as $(M_{T,t}\ M_{T,\bar{t}}\ M_{T,H})^{1/3}$, where $M_{T,i}$ is the transverse mass $\sqrt{M_i^2 + p_{T,i}^2}$, was used in the generation of the events at $\sqrt{s} = 7$ TeV. The factorization and the renormalization scales were set equal. The NLO MSTW2008 pdf set with 5 active flavours was used, together with the corresponding α_S and 68% C.L. uncertainty set.

* $H, A \to b\bar{b}$ with B.R.=1

* Jets were reconstructed through the anti-$k_\perp$ clustering algorithm, as implemented in FastJet 3.0.0, with R=0.5.

Cuts

A set of 20 observables was considered for the comparison, under the following four sets of cuts, inspired by previous papers [R. Frederix et al., 1104.5613] and [M.V.G. et al., 1108.0387] :

- set 0) No cut (inclusive analysis)
- set 1) $p_{\perp,H} > 200$ GeV, computed after showering and before H decay (boosted analysis)
- set 2) (i) $E^{\mathrm{j}}_{\perp,\mathrm{min}} = 25\,\mathrm{GeV}$ and (ii) $|\eta^{\mathrm{j}}| \leq 2.5$ for all jets (otherwise the jet is discarded), (iii) $\#\mathrm{jets} \geq 4$ for each event (hadronic-cut analysis)
- set 3) besides including cuts in set 2), (iv) we focused on the dileptonic channel, asking for at least one ℓ^+ and one ℓ^- with (v) $E^{\ell^\pm}_{\perp,\mathrm{min}} = 20\,\mathrm{GeV}$ and (vi) $|\eta^{\ell^\pm}| \leq 2.5$, whereas the transverse missing energy of the event was constrained to be (vii) $\not{E}_{\perp,\mathrm{min}} \geq 30\,\mathrm{GeV}$. Charged leptons not satisfying both cut (v) and cut (vi) were discarded in all events (all-cut analysis).

Selected distributions: scalar H + $t\bar{t}$

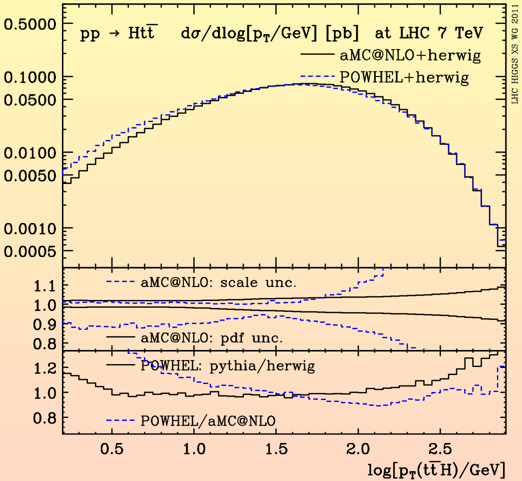

Figure: Transverse momentum of the Higgs-top-antitop system. In the upper inset the scale and pdf uncertainties computed by `aMC@NLO` interfaced to `HERWIG` are shown. The lower inset displays the ratio of `POWHEG-HELAC` over `aMC@NLO` and the ratio between the results computed by interfacing `POWHEG-HELAC` to `PYTHIA` and `HERWIG`.

$*$ sensitivity to the matching procedure: hard-scattering for large p_T and PS which resums large logs for small p_T

Selected distributions: pseudoscalar A + $t\bar{t}$

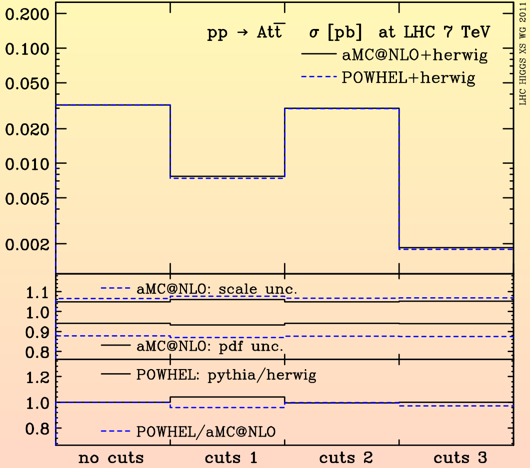

Figure: Total rates for pseudo-scalar Higgs boson production after the different cuts defined in previous slides in the no-cut configuration. Insets are defined as in previous figure.

Selected distributions: pseudoscalar A + $t\bar{t}$

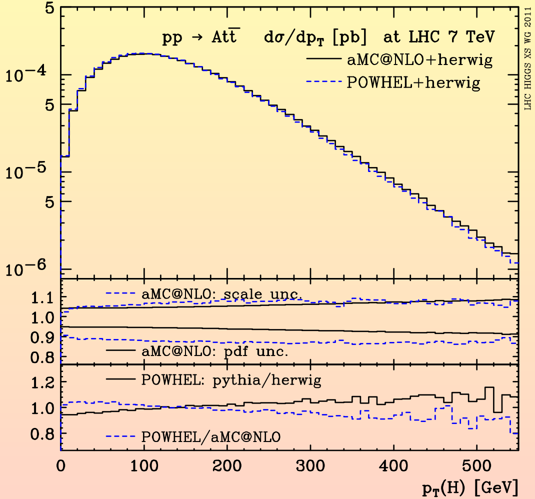

Figure: Transverse momentum of the pseudo-scalar Higgs boson in the no-cut configuration. Insets are defined as in previous figure.

Selected distributions: pseudoscalar A + $t\bar{t}$

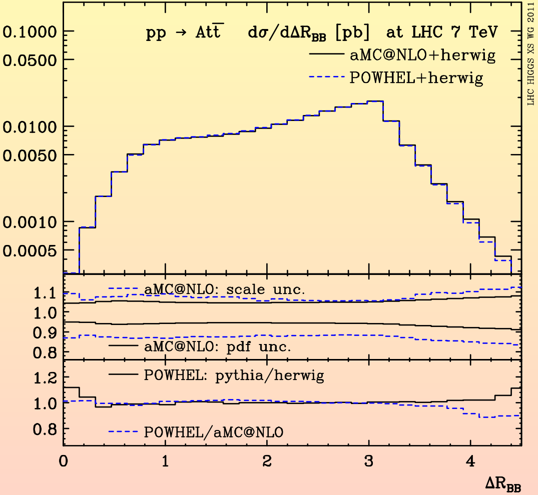

Figure: Separation in pseudo-rapidity and azimuthal angle of the two hardest lowest-lying B hadrons in the events (no-cut analysis). Insets are defined as in previous figure.

Selected distributions: pseudoscalar A + $t\bar{t}$

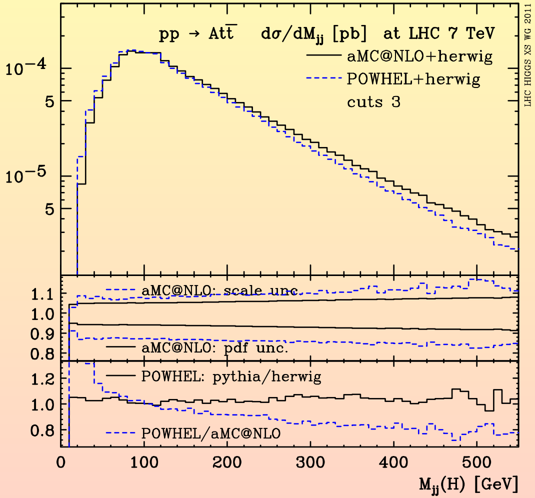

Figure: Invariant mass of all jet pairs passing the set 3) of cuts. Insets are defined as in previous figure.

Summary and Conclusions

∗ By means of the PowHelframework we have studied several processes at the NLO QCD + PS accuracy, involving top quark production and evolution. This allows for predictions at the hadron level, to be directly compared to experimental data.

∗ Examples of phenomenological analyses have been provided in this talk.

∗ During the comparisons with other groups we have realized the importance of a clear and agreed definition of observables and cuts, as well as in the assumptions used for the setup of the SMC. Even small differences can be crucial in producing different results!

∗ For most of the observables in the region non completely dominated by PS effects, the differences between different approaches (PowHel vs. aMC@NLO) turned out to be of the same order than the differences coming from the application of different SMC codes (PYTHIA vs. HERWIG) ($\sim$ 5 - 15%).

∗ More complete phenomenological studies require the analysis of all backgrounds, under the same conditions and cuts applied to signals.

∗ LHEF including events at the first radiation emission level are available on the web, ready to be decayed and showered by anybody (theoreticians or experimentalists): http://grid.kfki.hu/twiki/bin/view/DbTheory/.