

Standard Model Higgs boson production in association with a top anti-top pair at NLO with parton showering

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Abstract

We present predictions for the production cross section of a Standard Model Higgs boson in association with a $t\bar{t}$ pair at next-to-leading order accuracy using matrix elements obtained from the `HELAC-OneLoop` package. The NLO prediction was interfaced to the `PYTHIA` and `HERWIG` shower Monte Carlo programs with the help of `POWHEG-Box`, allowing for decays of massive particles, showering and hadronization, thus leading to final results at the hadron level.

PACS **12.38.-t** – Quantum ChromoDynamics

PACS **13.87.-a** – Jets in large- Q^2 scatterings

PACS **14.65.Ha** – Top quarks

PACS **14.80.Bn** – Standard Model Higgs boson

1 Introduction

In recent years a plethora of NLO QCD calculations have been presented in the literature. High-energy experiments, notably at the LHC, have and will be benefited by the progress in our computational ability to deal with higher order corrections to scattering amplitudes with many partons involved. In order though to get the optimum benefit and to produce predictions that can be directly compared to experimental data at the hadron level, a matching with parton showers and hadronization is ultimately inevitable.

According to the literature, two methods exist that deal with the matching of parton showers (PS) to matrix element (ME) calculations at NLO accuracy, MC@NLO [1, 2] and POWHEG [3, 4]. At the same time, several computational frameworks for NLO QCD calculations have emerged. In constructing a general interface of PS to ME computations with NLO accuracy, we have chosen to combine the POWHEG and HELAC-NLO [5] approach, respectively. The first application of our project was presented in Ref. [6].

In this letter we continue our investigation and validation of such an interface by studying Higgs boson production in association with a $t\bar{t}$ pair. There are several reasons to perform this work. On the phenomenological side, there is still interest to use this channel to search for Higgs boson in the low mass regime [7]. On the theoretical side, the appearance of recently developed tools as implemented in `amc@nlo` [8], also used in the analysis of Higgs boson production in association with a $t\bar{t}$ pair, offers a unique opportunity for cross-checking and validating our computations and the corresponding computer programs.

2 Method

We performed our calculations using the `POWHEG-Box` [9], a flexible computer framework implementing the POWHEG method, already used in the study of different processes also by other authors (among the others, the most recent applications include Ref. [10, 11, 12, 13]). In this work the following ingredients were requested and provided to `POWHEG-Box` as input:

- The flavor structures of the Born ($gg \rightarrow Ht\bar{t}$, $q\bar{q} \rightarrow Ht\bar{t}$, $\bar{q}q \rightarrow Ht\bar{t}$) and real radiation emission ($q\bar{q} \rightarrow Ht\bar{t}g$, $gg \rightarrow Ht\bar{t}g$, $\bar{q}g \rightarrow Ht\bar{t}\bar{q}$, $g\bar{q} \rightarrow Ht\bar{t}\bar{q}$, $\bar{q}q \rightarrow Ht\bar{t}g$, $qg \rightarrow Ht\bar{t}q$, $gq \rightarrow Ht\bar{t}q$) subprocesses ($q \in \{u, d, c, s, b\}$) were specified.
- The Born-level phase space was obtained by using the invariant mass of the $t\bar{t}$ quark pair and four angles.
- Squared ME's with all incoming momenta for the Born and the real-emission processes were built using amplitudes computed by `HELAC-OneLoop` [14], on the basis of skeleton structures generated by this same program and `HELAC-PHEGAS` [15], respectively. The ME's in the physical channels were obtained by crossing.
- Color structures for building the color-correlated Born amplitudes were taken from `HELAC-Dipoles` [16].
- Spin-correlated Born amplitudes were projected from the helicity basis to the Lorentz one by using the polarization vectors.

- `HELAC-OneLoop` was also used for computing the finite part of the virtual correction contributions in dimensional regularization, on the basis of the OPP method [17] complemented by Feynman Rules for the computation of the QCD R_2 Rational terms [18].

With this input `POWHEG-Box` was used to generate events at the Born level plus first radiation, stored in Les Houches Event Files (LHEF) [19]. Then, one can choose any shower Monte Carlo (SMC) program for generating events with hadrons, just by showering the previous ones and applying hadronization and decay models (it is worth mentioning that `POWHEG-Box` was written in the effort of being shower detail independent). We worked with both the `PYTHIA` [20, 21] and `HERWIG` [22, 23] SMC generators.

In the `POWHEG-Box` the first emission is the hardest one measured by transverse momentum which is also the ordering variable in `PYTHIA`. However, if the ordering variable in the shower is different from this one, such as in `HERWIG`, the hardest emission can be different from the first one. In such cases, in order to face this issue, `HERWIG` is constrained to discard shower evolutions (vetoed shower) with larger transverse momentum in all splittings occurring after the first emission, that is computed by `POWHEG-Box`. In addition, a truncated shower, simulating wide-angle soft emission before the hardest emission, is in principle also needed for `POWHEG` matching [3], but its effect turned out to be small [24]. As there is no implementation of truncated shower in `HERWIG` using external LHEF, the effect of the truncated shower is absent from our predictions.

3 Checks

The Born and the real ME's were tested in randomly chosen phase-space points against results from `HELAC-PHEGAS`. The consistency among real emission, Born, color-correlated and spin-correlated ME's was tested in randomly chosen real-emission phase-space regions, by examining the ratio between the real-emission amplitudes in soft and collinear limits and the corresponding subtraction terms, automatically computed by `POWHEG-Box` as approaching the related singularities.

The process presented here was studied extensively at the NLO accuracy in the literature [25, 26, 27, 28, 29], which enabled us to make detailed checks of our calculation.

	m_H , GeV	$\sigma_{\text{lit.}}^{\text{NLO}}$, fb	$\sigma_{\text{PH}}^{\text{NLO}}$, fb
TeVatron ($\sqrt{s} = 2$ TeV)	120	4.857(8)	4.851(3)
	140	2.925(4)	2.918(2)
	160	1.806(2)	1.797(2)
	180	1.132(1)	1.128(1)
LHC ($\sqrt{s} = 14$ TeV)	120	701.5(18)	701.3(8)
	140	452.3(12)	452.8(5)
	160	305.6(8)	305.0(4)
	180	214.0(6)	213.9(3)

Table 1: Comparison of the NLO cross sections by `POWHEG-HELAC` (PH) to the predictions of Ref. [26] (lit) at the default scale $\mu_R = \mu_F = \mu_0$.

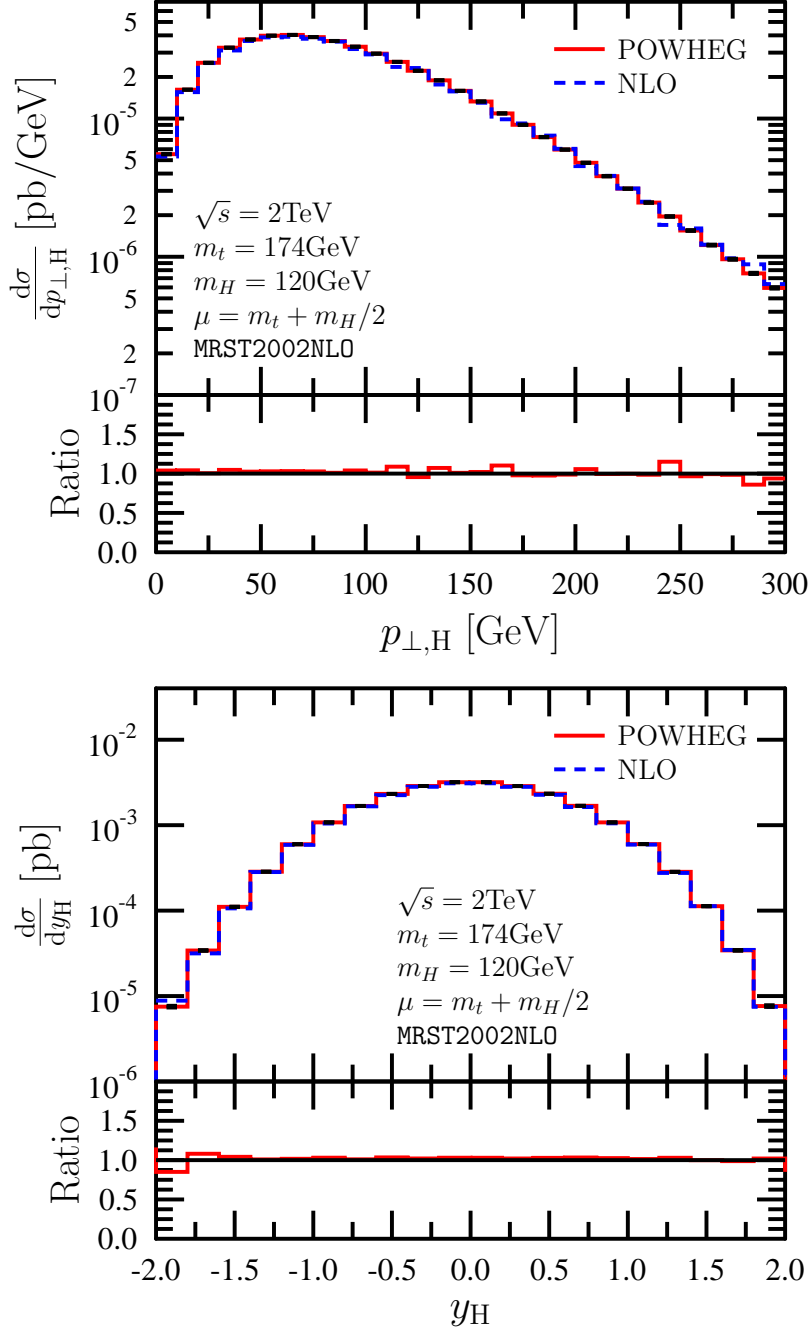


Figure 1: Transverse momentum and rapidity distributions of the Higgs boson at the Tevatron from our calculation by means of POWHEG-HELAC (POWHEG) and from Ref. [26] (pure NLO). The lower panels show the ratio of the results (POWHEG/NLO).

As for the virtual contribution, we compared our amplitudes to the predictions of MADLOOP using the input parameters and phase space point specified in Ref. [30] for different renormalization scale choices [31], and in all cases we found agreement up to 5–6 digits.

We then compared the cross-sections at the NLO accuracy to the predictions of Ref. [26]. At this purpose, we used the MRST2002n1o [32] PDF set, provided by LHAPDF [33], with a 2-loop running α_s , 5 light flavours and $\Lambda_5^{\overline{\text{MS}}} = 239 \text{ MeV}$, and the following parameters: $m_H = 120 \text{ GeV}$, $m_t = 174 \text{ GeV}$, $G_F = 1.16639 \cdot 10^{-5} \text{ GeV}^{-2}$. The renormalization and factorization scales were chosen equal to μ , where μ was varied in the $\mu_0/4 - 4\mu_0$ interval, with default scale being $\mu_0 = m_t + m_H/2$. The calculations were performed at the planned LHC energy of $\sqrt{s} = 14 \text{ TeV}$. The results of this comparison are presented in Table 1, showing agreement. We also made a comparison to the predictions of Ref. [29], using the CTEQ5M PDF set from LHAPDF, a 2-loop running α_s with $\alpha_s(M_Z) = 0.118$, m_t and G_F as given above, and again found agreement within their quoted uncertainty.

Finally, we also compared differential distributions from events already including first radiation emission with the NLO predictions of Ref [26]. We found agreement for all distributions presented in that paper. As examples, we show in Fig.1 the transverse momentum and rapidity distributions of the Higgs boson in the Tevatron setup ¹.

4 The effect of the shower

In interfacing NLO calculations to SMC programs we mainly aim at estimating the effects of showers and hadronization, therefore, we analyzed the events at two different stages of evolution:

Decay: starting from the events collected in LHEF produced by POWHEG-HELAC, we just included on-shell decays of t-quarks and the Higgs boson, as implemented in PYTHIA, and further decays of their decay products, like charged leptons (the τ is assumed to be unstable), W and Z , turning off any shower and hadronization effect.

Full SMC: decays, showering evolution and hadronization have been included in our simulations, using both PYTHIA and HERWIG.

In both SMC setup muons (default in PYTHIA) and neutral pions were assumed as stable particles. All other particles and hadrons were allowed to be stable or to decay according to the default implementation of each SMC. Quark and Higgs masses, as well as W , Z masses and total decay widths, were tuned to the same values in PYTHIA and HERWIG. On the other hand, each of the two codes was allowed to compute autonomously partial branching fractions in different decay channels for all unstable particles and hadrons. Multiparticle interaction effects were neglected (default in HERWIG). Additionally, the intrinsic p_T spreading of valence partons in incoming hadrons in HERWIG was assumed to be 2.5 GeV. Considering this setup, we found agreement between PYTHIA and HERWIG predictions within 5%, except in bins where the statistics is very small. Beside the conceptual differences in the parton shower and hadronization algorithms between the two SMC generators, written on the basis of different theoretical ideas (p_\perp vs. angular ordering, string model vs. cluster hadronization and preconfinement), a possible origin of this overall small discrepancy is the absence of the truncated shower in the HERWIG

¹ Note that these comparisons refer to distributions without normalization, as opposed to the plots in the original publication.

prediction. Unfortunately, however, as already mentioned, we cannot check the last point within the POWHEG-Box framework. In any case, the modest entity of the discrepancy means that the effect of the truncated shower, not included in our analysis, is small. Further explanations of small discrepancies can also be related to the different decay channel scheme and branching fractions in the two SMC codes.

In our computation, we adopted the following parameters: $\sqrt{s} = 7 \text{ TeV}$, CTEQ6.6M PDF set from LHAPDF, with a 2-loop running α_s , 5 light flavours and $\Lambda_5^{\overline{\text{MS}}} = 226 \text{ MeV}$, $m_t = 172 \text{ GeV}$, $m_H = 120 \text{ GeV}$, $G_F = 1.16639 \cdot 10^{-5} \text{ GeV}^{-2}$. The renormalization and factorization scales were chosen equal to $\mu_0 = m_t + m_H/2$. We decided to switch on all possible decay channels of the Higgs boson, implemented in the SMC programs.² We used the last version of the SMC codes: PYTHIA 6.425 and HERWIG 6.520.

We studied the effect of the full SMC by comparing distributions at the decay and SMC level. As the number of particles is very different at the end of the two stages, we first made such a comparison without any selection cut, in order to avoid the introduction of any bias. This way the cross-section at all levels is indeed exactly the same. We found $\sigma_{\text{POWHEG-HELAC}} = \sigma_{\text{POWHEG-HELAC+DECAY}} = \sigma_{\text{POWHEG-HELAC+SMC}} = 95.872 \pm 0.007 \text{ fb}$ (here and in all following σ predictions the quoted uncertainties are the statistical ones only). As an illustrative example, we present the distributions of the transverse momentum and rapidity of the hardest jet, p_{\perp,j_1} and y_{j_1} , in Fig. 2 and Fig. 3, respectively. The jets are reconstructed through the anti- k_{\perp} algorithm with $R = 0.5$, by using FastJet 2.4.3 [34]. One can observe a rather significant softening in the transverse momentum spectrum as going from results at the decay level to full SMC ones. On the other hand, the effect of the shower on the rapidity of the hardest jet is almost negligible and rather homogeneous. We distinguished several classes of jets including final state emissions, according to their origin: jets that can be traced back to (i) first radiation emissions, (ii) the decay products of the Higgs boson, (iii) the decay products of the top and antitop quarks, (iv) a mixing of the previous ones. In particular, main contributions to the p_{\perp,j_1} spectrum shown in Fig. 2 are due to jets of the (iv) and (iii) class. As for the y_{j_1} distribution, the tails are dominated by jets of the (iv), (i) and (iii) classes.

In Ref. [30] the invariant mass, m_{BB} , and the separation in the rapidity–azimuthal-angle plane of the two hardest lowest-lying B-hadrons, ΔR_{BB} , were studied, by choosing a dynamical scale for the generation of the hard-scattering events and by taking into account only the $H \rightarrow b\bar{b}$ decay channel. Besides computing all p_T distributions already presented in that paper, always finding agreement, we also computed the aforementioned B-hadron distributions reproducing the same simulation setup and without applying any cut, considering only the $H \rightarrow b\bar{b}$ decay channel, as well as all channels. In the former, we found agreement with the predictions of Ref. [30]. The effect of the remaining channels, not studied in that work, produces an increase in the region below 80 GeV in the m_{BB} spectrum and only for large ΔR_{BB} , as shown in Figs. 4 and 5. Pairs of B-hadrons both including quarks that can be traced back to Higgs decays only populate the region of the m_{BB} spectrum below m_H . The region above m_H is instead dominated by pairs with at least one B-hadron that can be traced back to a (anti)top decay.

The effects of the decay and shower also depend on the selection cuts. While the typical selection cuts include both leptons and hadrons, we started with a restricted

²In PYTHIA there are two more decay channels than in HERWIG, and partial decay fractions in each leptonic, bosonic and partonic channel differ in the two codes.

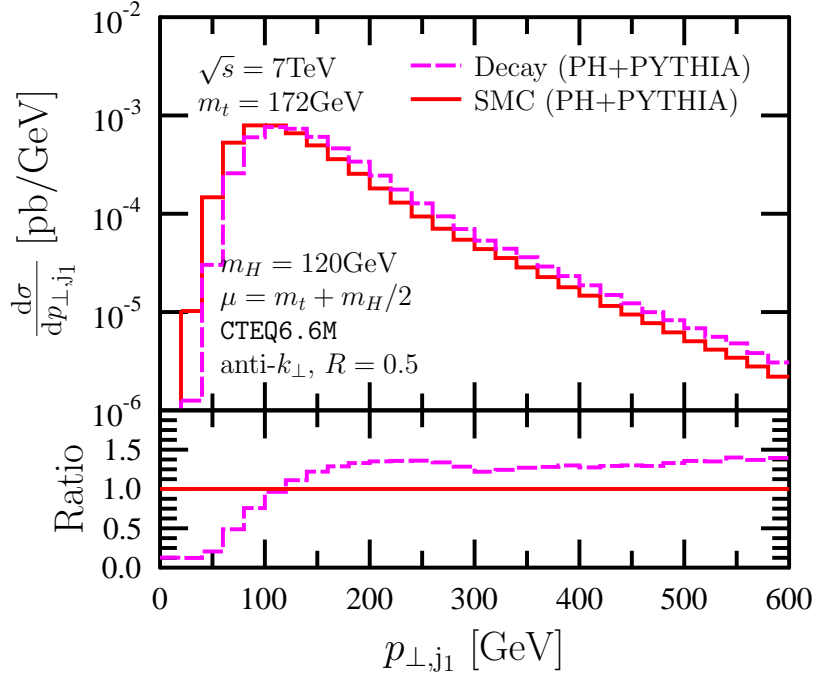


Figure 2: Transverse momentum distribution of the hardest jet. The results at the decay level (dashed line) are compared to the ones at the SMC level (solid line), obtained by interfacing POWHEG-HELAC to PYTHIA . No selection cuts were applied.

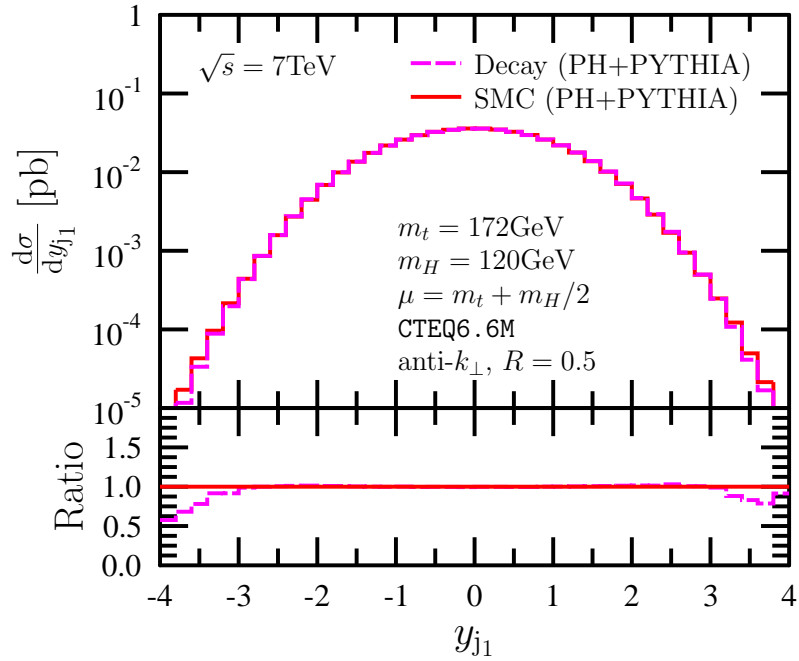


Figure 3: The same as Fig. 2, as for the rapidity of the hardest jet.

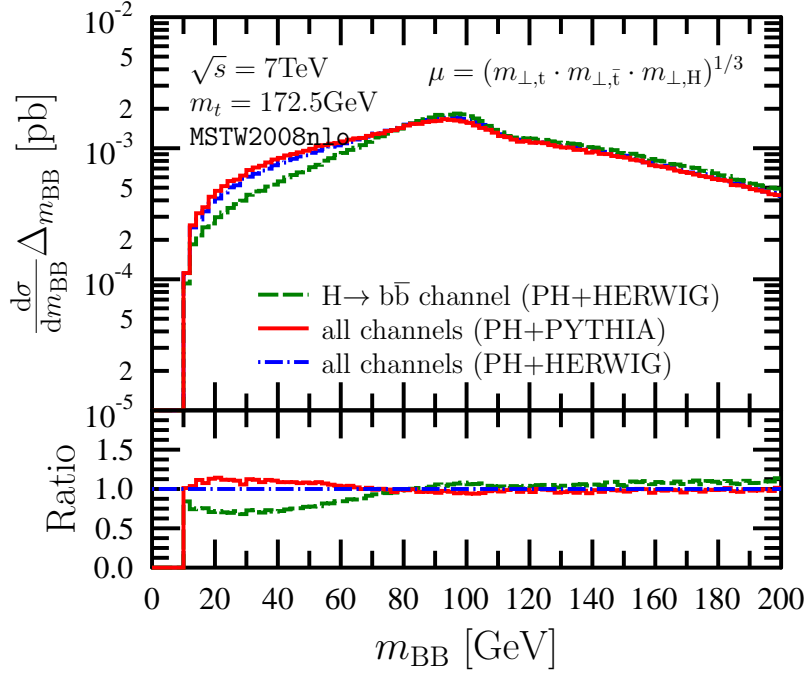


Figure 4: Invariant mass distribution of the two hardest lowest-lying B hadrons at the SMC level. These results are presented in sigma per bin, just to allow an easier comparison with the results of Ref. [30], having been obtained in the same setup, without applying any cut. The effects of including all H decay channels, with respect to the case of a single $H \rightarrow b\bar{b}$ channel (dashed line), were computed by interfacing POWHEG-HELAC to both PYTHIA (solid line) and HERWIG (dash-dotted line).

set, not involving any leptonic cut, in particular as for the number of leptons. This is motivated by the fact that this number can be quite different at the decay and shower level, as the shower produce many secondary leptons. Thus, coming back to our setup, we considered and implemented cuts only on jet variables: (i) $p_{\perp,\min}^j = 20 \text{ GeV}$ and (ii) $|y^j| \leq 2.5$ for all jets, (iii) $\#\text{jets} \geq 4$ in each event. We show the distribution of the scalar sum of all transverse momenta in the event, H_{\perp} in Fig. 6. We can see that the spectrum becomes softer due to showering effects, with respect to the one computed at the decay level, as can be understood on the basis of PS physics. The same is true and even more evident if one singles out the hadronic component of H_{\perp} , as well (not shown). On the other hand, the effects of the shower on the (anti-)lepton transverse momentum, p_{\perp}^{ℓ} , and the missing transverse momentum, p_{\perp}^{miss} , as shown in Figs. 7 and 8, are small and rather uniform, except for a significant increase for small values, which is due to secondary leptons produced in the shower. The cross-sections at the decay and at the SMC level, after the hadronic cuts listed above, amount to $\sigma_{\text{POWHEG-HELAC+DECAY}} = 92.29 \pm 0.01 \text{ fb}$, $\sigma_{\text{POWHEG-HELAC+PYTHIA}} = 90.46 \pm 0.01 \text{ fb}$ and $\sigma_{\text{POWHEG-HELAC+HERWIG}} = 90.99 \pm 0.01 \text{ fb}$.

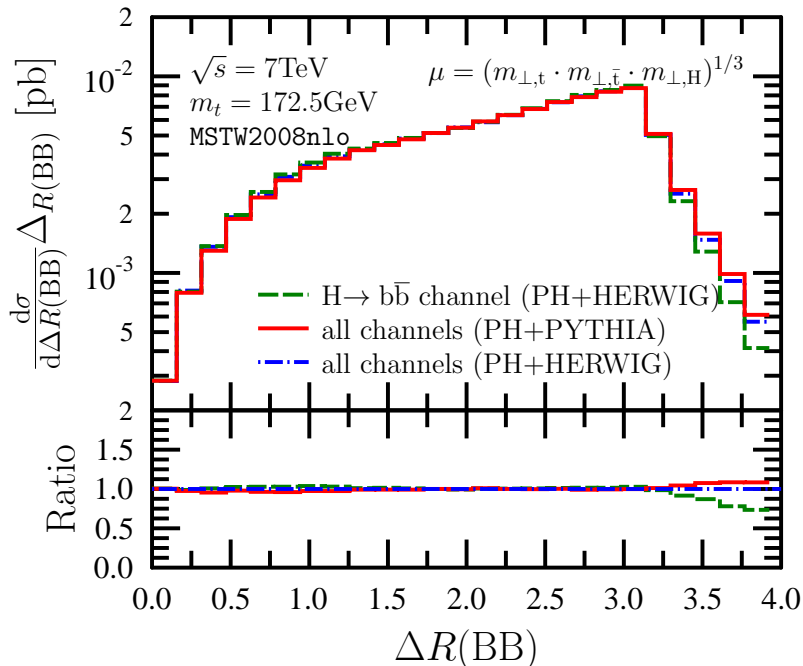


Figure 5: The same as Fig. 4, as for the azimuth-rapidity distance correlations of the two hardest lowest-lying B hadrons.

5 Predictions

In this section we present predictions for $Ht\bar{t}$ production with parton shower and hadronization effects at LHC. In addition to the jet cuts (i–iii) mentioned above, we also applied selection cuts on the leptonic variables:³ (iv) we focused on the dileptonic channel, asking for exactly one ℓ^+ and one ℓ^- with (v) $p_{\perp,\min}^{\ell^\pm} = 20$ GeV and (vi) $|y^{\ell^\pm}| \leq 2.5$, whereas the transverse missing energy of the event was constrained to (vii) $\cancel{E}_{\perp,\min} \geq 30$ GeV.

In Fig. 9 we present the distribution of the invariant mass of all jet pairs. Here the effect of the shower is again quite significant. In particular, there is a small bump around the Higgs mass, as already noticed in the literature [35], visible in the data at the decay level, which is completely washed out when PS is included. The same is true for the invariant mass distribution of the two hardest jets (not shown).

The cross-section after cuts, at the SMC level, were found to be $\sigma_{\text{POWHEG-HELAC+PYTHIA}} = 5.376 \pm 0.010$ fb and $\sigma_{\text{POWHEG-HELAC+HERWIG}} = 5.521 \pm 0.011$ fb.

One of the biggest differences in the results produced by PYTHIA and HERWIG interfaced to the POWHEG-Box noticed in Ref. [12] in the study of a different process was the observation that HERWIG gives rise to hard jets more central than PYTHIA. We observe the same trend in our results, but by far to a lesser extent. In particular, in the bins around zero rapidity the ratio between the rapidity distributions of POWHEG-HELAC + HERWIG and POWHEG-HELAC + PYTHIA found in our study amounts to maximum 1.05, both in case of the hardest and the second hardest jet. On the other hand, the agreement between the two SMC, as for the rapidity distributions of leptons and antileptons, was found to be

³Similar cuts are applied by the LHC experiments.

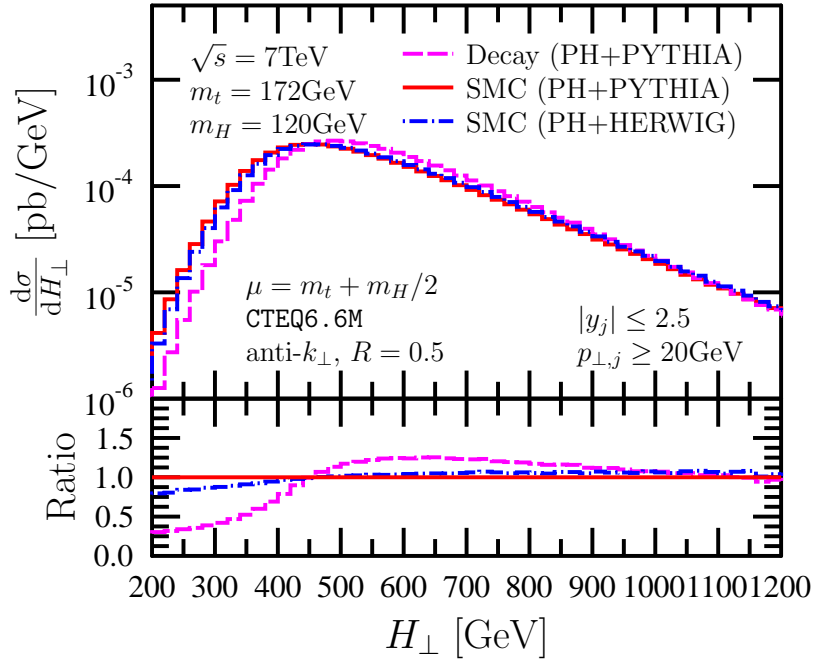


Figure 6: Distribution of the sum of the transverse momenta of all particles, at the decay level (dashed line) and at the SMC level, as obtained by interfacing POWHEG-HELAC to PYTHIA (solid line) and HERWIG (dash-dotted line). Only hadronic cuts were applied.

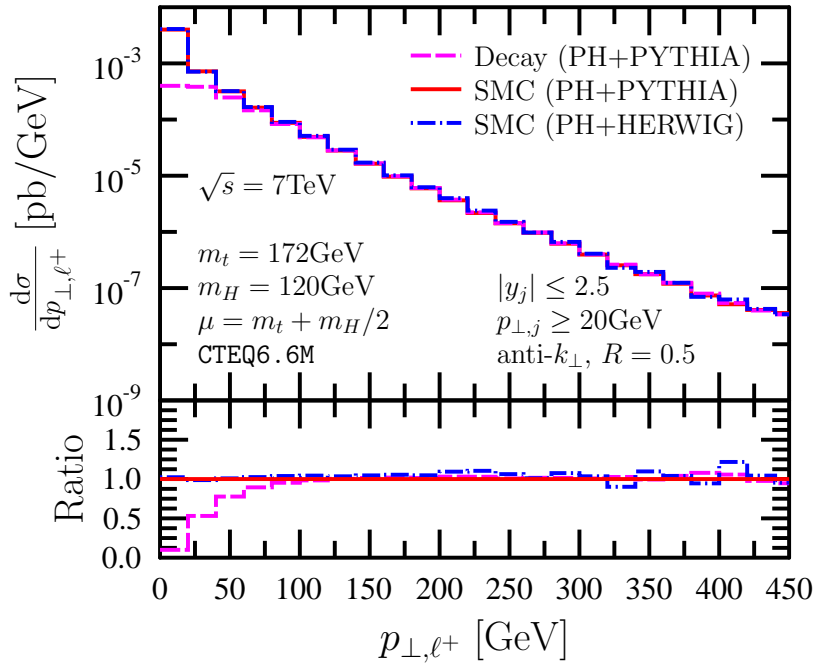


Figure 7: The same as Fig. 6, as for the transverse momentum of all antileptons.

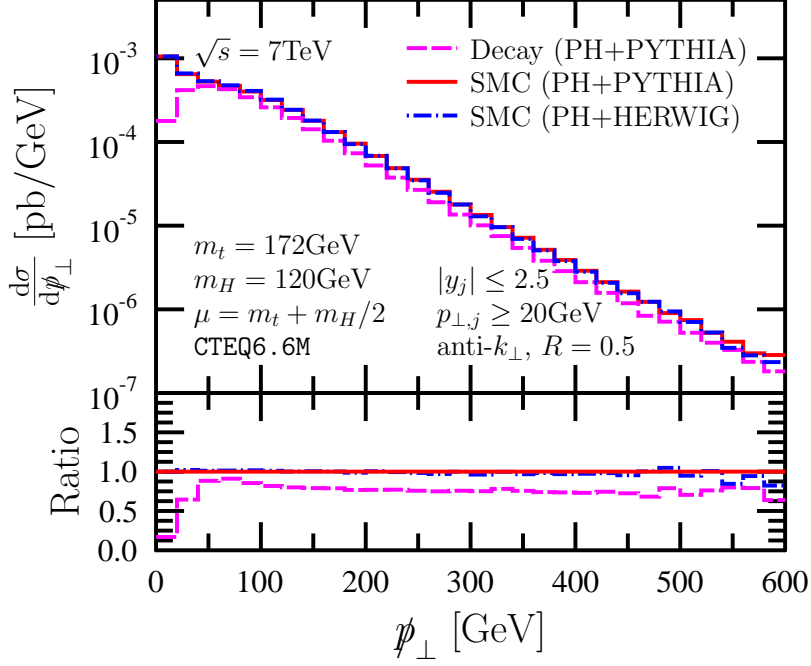


Figure 8: The same as Fig. 6, as for the total missing transverse momentum.

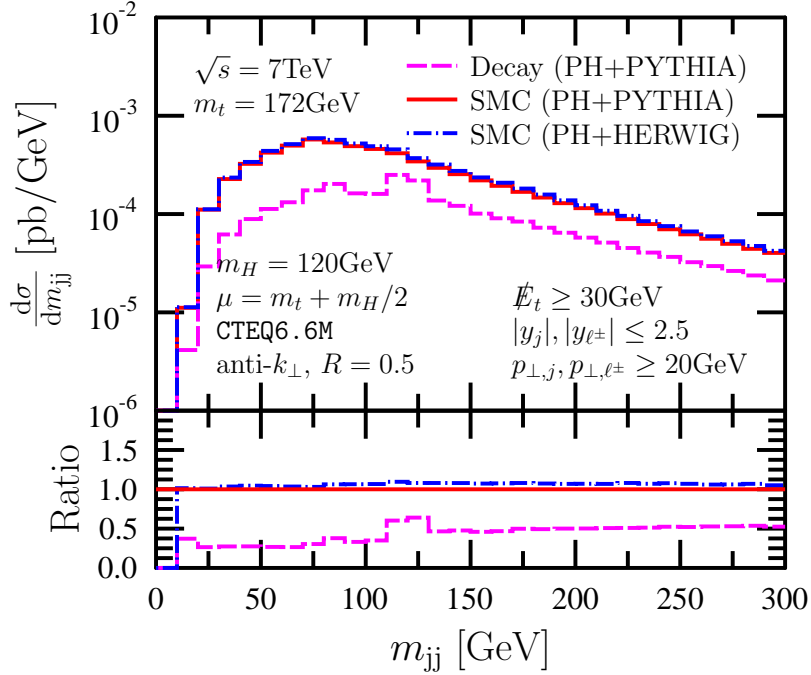


Figure 9: Invariant mass distribution of all jet pairs. Results at the decay level (dashed line) are shown together with results after showering and hadronization, obtained by interfacing POWHEG-HELAC predictions to both the PYTHIA (solid line) and HERWIG (dash-dotted line) SMC. The full set of hadronic and leptonic cuts was applied.

even closer.

6 Conclusions

We would like to conclude this letter by emphasizing that interfacing NLO calculations, as structured in HELAC-NLO, with PS and hadronization effects, within the POWHEG framework, open the exciting possibility of realistic, precise and reliable simulations of pp hard-scattering collisions, leading to multiparticle production, up to the hadron level, as detected in the accelerator experiments. We have presented predictions for the signal, $pp \rightarrow t\bar{t}H$ production, illustrating their consistency with existing calculations, as well as the phenomenological potential of our approach. A thorough analysis, including the most important backgrounds, notably $pp \rightarrow t\bar{t}b\bar{b}$, within the same framework, is in progress and will be reported elsewhere. The event files produced by POWHEG-HELAC, together with further detail and results of our project, are available at <http://grid.kfki.hu/twiki/bin/view/DbTheory/TthProd>.

Acknowledgements

This research was supported by the HEPTOOLS EU program MRTN-CT-2006-035505, the LHCPheNet network PITN-GA-2010-264564, the Swiss National Science Foundation Joint Research Project SCOPES IZ73Z0_1/28079, the MEC project FPA 2008-02984 (FALCON), and the TÁMOP 4.2.1./B-09/1/KONV-2010-0007 project. We are grateful to M. Krämer for providing us the data files with their NLO predictions [26]. M.V.G. is grateful to the Departamento de Física Teórica y del Cosmos of Granada University for hospitality. A.K. is grateful to G. Bevilacqua for useful discussions on the original HELAC programs.

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