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$t\bar{t}$ + hard X hadroproduction with PowHel*

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We present the PowHel framework to make theoretical predictions for the hadroproduction of $t\bar{t}$ + hard X ($X = H, A, Z$, jet) as obtained by matching numerical computations at NLO accuracy in QCD with Shower Monte Carlo programs. PowHel relies on the POWHEG-BOX with input of matrix elements produced by the HELAC-NLO. It produces events according to the Les Houches accord that can be used as input in shower Monte Carlo programs such as PYTHIA and HERWIG to simulate parton showering and hadronization.

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The t-quark plays a special role in the physics programs of modern colliders such as the TeVatron or LHC. Many aspects of this special status were discussed extensively in the literature. Here we mention only two interesting, yet unexplained facts that could be accidental or hints of some deeper underlying physics. One is that the t-quark is the heaviest one among the known fundamental fermions with Yukawa coupling $y_\mathrm{t} = 1$ within statistical uncertainty of the measurements [1]. The other is that the geometric mean of the mass of the t-quark and that of the Z-boson is equal to the mass of the recently discovered boson at the LHC [2, 3] within statistical uncertainty of the measurements. While these interesting observations wait for explanations, it appears clear that the t-quark plays an essential role in Higgs and beyond Standard Model physics.

Presently, there is a wealth of measurements ongoing at the LHC experiments targeting important characteristics related to the t-quark (such as production cross section, mass, width, t-$\bar{\mathrm{t}}$ mass difference, charge, charge asymmetry, anomalous couplings etc.). In the future the coupling of the t-quark to Standard Model (SM) bosons will be measured, as well as it will be used as a discovery tool for possible new physics beyond the SM. All these measurements will require precision predictions for $\mathrm{t\bar{t}}$ + hard X final states, where X denotes a SM boson, or more complex hard object, such as a $\mathrm{b\bar{b}}$-pair, or 2 jets. In our project [4] we set the goal of providing a framework for generating events according to the Les Houches accord (LHE's) [5] for such final states. The advantage of the LHE's is that those can be used in a shower Monte Carlo (SMC) program to generate events at the hadron level which give distributions formally correct at the next-to-leading order (NLO) accuracy in perturbation theory.

In order to construct a generic interface between SMC's and cross sections at the NLO accuracy, we have chosen to combine the HELAC-NLO [6] (for NLO computations) and POWHEG (for the matching of NLO with parton shower) [7, 8] approaches as implemented in the `HELAC-NLO` [9] and `POWHEG-BOX` [10] codes, respectively. There are already several applications of this combined framework `PowHel` to the processes $pp \to \mathrm{t\bar{t}}$ + jet [11], $pp \to \mathrm{t\bar{t}}+H$ [12], $pp \to \mathrm{t\bar{t}}+Z$ [13, 14] and $pp \to \mathrm{t\bar{t}}+W^\pm$ [15].

There are some advantages of such an approach as compared to making predictions at the NLO accuracy. As we generate events at the hadron level, the predictions are clearly closer to what is measured in experiments, and a realistic experimental analysis becomes feasible. The t-quarks decay almost immediately, only their decay products are detected. Also the parton shower can have a significant effect, especially in Sudakov-regions. For the user event generation with `PowHel` is faster than running an NLO code, but we also deliver the events on request.

There is also an important advantage of the POWHEG method used for the NLO + PS matching. One can prove that the formal accuracy of a differential distribution for an observable O obtained from the LHE's is

$$\frac{\mathrm{d}\sigma_\mathrm{LHE}}{\mathrm{d}O} = \frac{\mathrm{d}\sigma_\mathrm{NLO}}{\mathrm{d}O} + \mathrm{O}(\alpha_\mathrm{s}) \int \mathrm{d}\Phi_R R(\Phi_R) \Big[\delta(O(\Phi_R) - O) - \delta(O(\Phi_B) - O)\Big]. \qquad (1)$$

In this equation Φ_B and Φ_R denote the phase space for the Born cross section and real correction $R(\Phi_R)$, respectively. The size of the $\mathrm{O}(\alpha_\mathrm{s})$ factor scales with the NLO K-factor. For all the final states we studied so far we checked the ratios of the LHE and NLO predictions and found agreement within at most several per cent. We show two representative comparisons in Fig. 1, where we show the first application of the POWHEG method to the process $pp \to \mathrm{t\bar{t}} \to e^+\nu_e\mu^-\bar{\nu}_\mu\mathrm{b\bar{b}} + X$. The

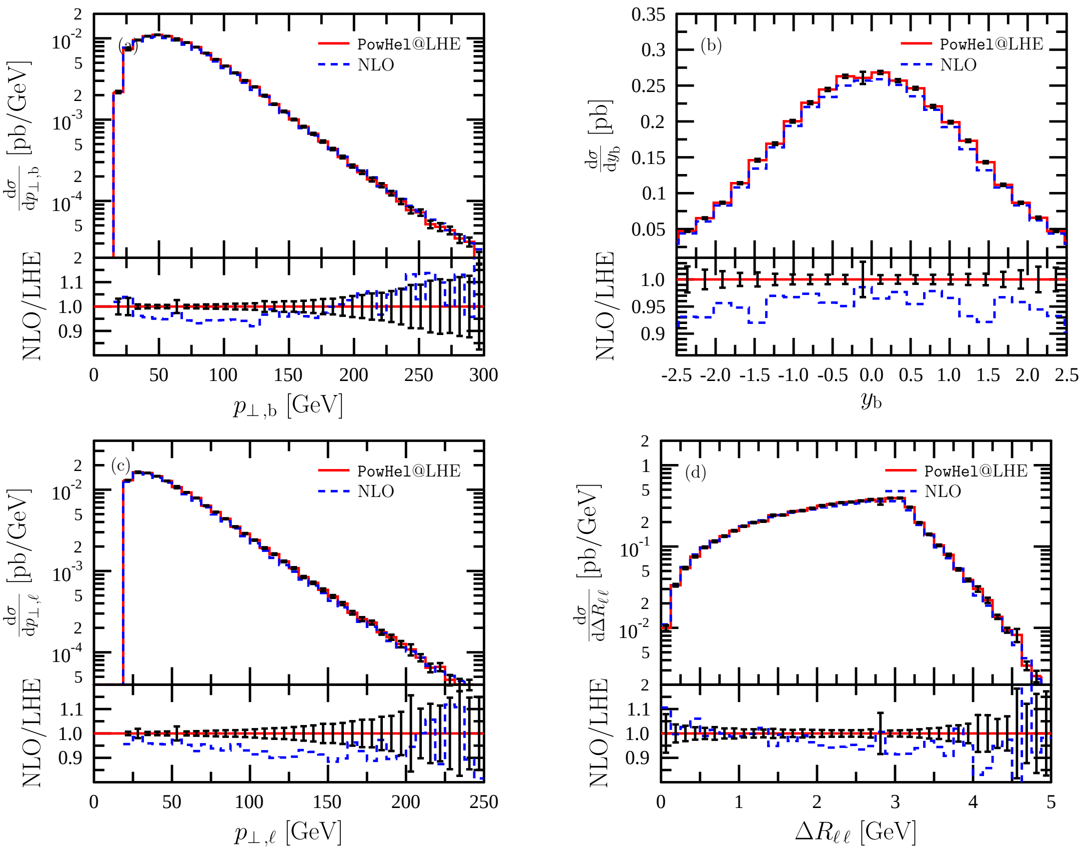

Figure 1: Distributions of a) transverse momentum of the b-quark, b) rapidity of the b-quark, c) transverse momentum of the muon, d) ΔR-separation of the positron and the muon in $pp \to t\bar{t} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$. The insets below each plot show the predictions NLO/PowHel with error bars representing the statistical uncertainty of the LHE's.

predictions at the NLO accuracy are taken from Ref. [16], while the LHE's were generated by `PowHel` using the same set of parameters. The computation uses complex masses, thus allowing for including spin-correlations and the complete off-shell effects at NLO accuracy.

Once the agreement between the predictions from the LHE's and at NLO is established, one can use the LHE's for studying the effect of the parton shower (PS) as well as that of the full SMC. For this purpose we use the last version of the SMC programs, `PYTHIA` 6.426 [17] and `HERWIG` 6.520 [18]. In order to study the effect of the PS, one can use the SMC's for letting the heavy particles decay and then switch on or off the PS. Similarly, in order to study the effect of hadronization one can use the SMC for the decays and PS and then switching on or off hadronization. We can select hadronic or leptonic decays of the t-quarks. In the former case the hadrons are combined into jets. For jet reconstruction we use the anti-$k_\perp$ algorithm [19] as implemented in `FastJet` [20].

For demonstrating the listed options, we choose the process $pp \to t\bar{t} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$ and for observable the ΔR-separation of the positron-muon pair ($\Delta R_{e^+\mu^-}$). For this process at vanishing transverse momentum of the b-quarks or vanishing invariant mass of the $b\bar{b}$-pair the Born cross section becomes singular (our b-quarks are massless). While this can never happen in a LO computation due to the selection cuts, it is a problem in the POWHEG method because the selection cuts can only be applied after event generation. The traditional way of treating this problem is the introduction of a generation cut [21]. We use $p_{\perp,\mathrm{b}} \geq 2\,\mathrm{GeV}$ for both the anti-b and b-quark and a cut $m_{\mathrm{b\bar{b}}} \geq 1$ GeV. With these cuts the LO cross section becomes finite.

Taking into account that physical cuts should always be well above the technical ones, we consider the following set of physical cuts:

1. Each jet is required to have transverse momentum $p_{\perp,j} > 20\,\mathrm{GeV}$ and pseudorapidity $|\eta_j| < 5$, otherwise it is not counted among the jets.
2. Each of the jets satisfying the 1st condition, to be classified as a b- or $\mathrm{\bar{b}}$-jet, is required to have $|\eta_{\mathrm{b}}| < 3$, due to the geometry of the tracking system.
3. We require at least one b-jet and one $\mathrm{\bar{b}}$-jet.
4. Each charged lepton is required to have $p_{\perp,\ell} > 20$ GeV and $|\eta_\ell| < 2.5$, otherwise it is not counted among the leptons.
5. We require at least one charged lepton and one charged anti-lepton, that are isolated from all jets by requiring $\Delta R(\ell, j) > 0.4$ (1.2) in the azimuthal angle–pseudorapidity plane. If there are more leptons that pass cut 4, those are kept without isolation from the jets.
6. We require a minimum missing transverse momentum $\not{p}_\perp > 30\,\mathrm{GeV}$.

These cuts present some modifications with respect to those in Ref. [16] providing predictions at the NLO accuracy.

In Fig. 2 we show four different plots for the chosen observable. For making these predictions we used the value $m_{\mathrm{t}} = 173.2\,\mathrm{GeV}$ for the t-quark mass [22]. Correspondingly, we use $\Gamma_{\mathrm{t}}^{\mathrm{NLO}} = 1.32\,\mathrm{GeV}$. While the b-quark masses were set zero in generating the hard-scattering amplitudes, these were kept to their default values implemented in `PYTHIA` in the SMC evolution to B-hadrons. Quark masses in `HERWIG` were set to the same values as in `PYTHIA` default. In the configuration of the SMC, for all other mass and width parameters, including light quark masses, we used the default values already implemented. We use the `CTEQ6.6m` parton distribution functions from `LHAPDF` with $\Lambda_5 = 226\,\mathrm{MeV}$ and strong coupling α_s computed with 2-loop running. The renormalisation and factorisation scales were set equal to m_{t}.

First, in Fig. 2.a we compare the predictions obtained from the LHE's with two different ways of generation: the dotted line is obtained from on-shell $\mathrm{t\bar{t}}$ -events with decays of the t-quarks performed by `PYTHIA`, while the solid line is obtained from the LHE's of the process $pp \to \mathrm{t\bar{t}} \to e^+\nu_e\mu^-\bar{\nu}_\mu\mathrm{b\bar{b}}+X$ with full information of spin-correlations and off-shell effects at NLO accuracy. We find significant, up to 20 %, effect due mainly to the spin-correlations below $\Delta R_{e^+\mu^-} < 2\pi$ (the off-shell effects are small [23]).

Second, in Fig. 2.b we compare the predictions obtained from the LHE's (dotted line) and after full SMC with `PYTHIA` (solid line) for the process $pp \to \mathrm{t\bar{t}} \to e^+\nu_e\mu^-\bar{\nu}_\mu\mathrm{b\bar{b}}+X$. We find that the effect of the PS (mainly) and of the hadronization (to less extent, but not shown separately here) is an almost uniform 30 % decrease of the cross section. Thus the SMC has a significant effect that should be taken into account in comparisons with data.

Third, in Fig. 2.c we compare the predictions after full SMC with two different ways of generation: the dotted line is obtained from on-shell $\mathrm{t\bar{t}}$ -events, while the solid line is obtained from the

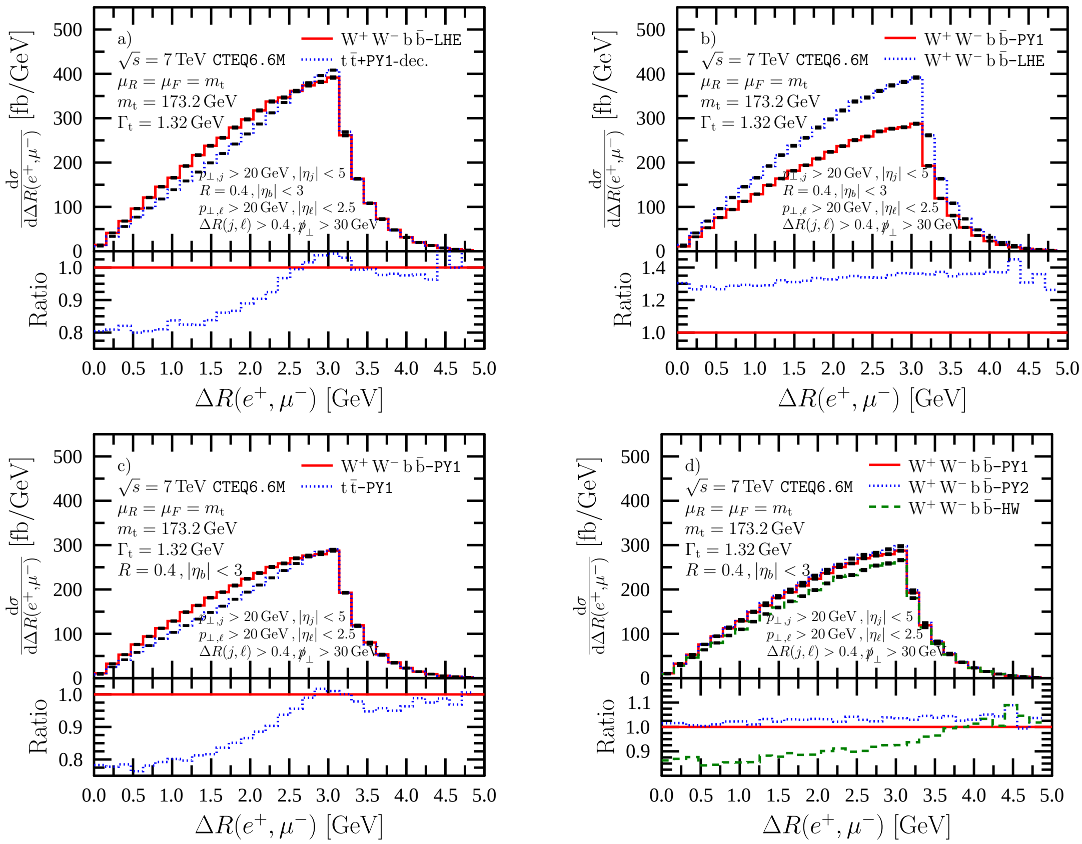

Figure 2: Distributions of ΔR-separation of the positron and the muon. For a detailed explanation see the text. The insets below each plot show the ratio of the predictions.

process $pp \to t\bar{t} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$. We see that the effect of the spin-correlations and off-shell effects seen at the LHE's is only slightly changed by the SMC.

Finally, in Fig. 2.d we study the effect of various SMC programs: the untuned version of `PYTHIA` (denoted by `PY1`, the solid line), providing a virtuality ordered PS, and a version tuned to the Perugia 2011 set of values [24], one of the most recent tunes, providing a $p_\perp$-ordered PS, updated on the basis of recent LHC data (denoted by `PY2`, the dotted line). The dashed line was obtained by using `HERWIG`-6.520 (denoted by `HW`). While the two `PYTHIA`-versions give very similar predictions, `HERWIG` gives smaller cross sections by up to 15 % at small separations.

With Fig. 2 we only intended to present the many options one can study with the events generated by `PowHel`. More detailed analysis for this process is in preparation. We made similar studies for other processes involving the hadroproduction of a $t\bar{t}$ -pair in association with some hard SM boson. In general we found that the effect of the PS is often significant and has to be taken into account when comparison to data is performed.

We expect that our LHE's available at our web page [25] constitute a useful starting point for performing an analysis for final states involving a $t\bar{t}$ -pair at hadron colliders. For generating events with other values of the (physical and non-physical) parameters the `PowHel` code, also available on the web page, can be downloaded, or we can provide the events on request.

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PoS(LL2012)057