The Monte Carlo Event Generator AcerMC and package AcerDET

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Abstract

The **AcerMC** Monte Carlo Event Generator is dedicated for the generation of Standard Model background processes at *pp* LHC collisions. The program itself provides a library of the massive matrix elements and phase space modules for generation of selected processes. The hard process event, generated with one of these modules, can be completed by the initial and final state radiation, hadronisation and decays, simulated with either `PYTHIA`, `ARIADNE` or `HERWIG` Monte Carlo event generator and (optionally) with `TAUOLA` and `PHOTOS`. Interfaces to all these packages are provided in the distribution version. The matrix element code has been derived with the help of the `MADGRAPH` package. The phase-space generation is based on the multi-channel self-optimising approach using the modified Kajantie-Byckling formalism for phase space construction and further smoothing of the phase space was obtained by using a modified `ac-VEGAS` algorithm.

1 Introduction

The physics programme of the general purpose LHC experiments, ATLAS [1] and CMS [2], focuses on the searches for the *New Physics* with the distinctive signatures indicating production of the Higgs boson, SUSY particles, exotic particles, etc. The expected environment will in most cases be very difficult, with the signal to background ratio being quite low, on the level of a few percent after final selection in the signal window.

Efficient and reliable Monte Carlo generators, which enable one to understand and predict background contributions, are becoming key elements in the discovery perspective. As the cross-section for signal events is rather low, even rare Standard Model processes might become the overwhelming backgrounds in such searches. In several cases, generation of such processes is not implemented in the general purpose Monte Carlo generators, when the complicated phase space behaviour requires dedicated (and often rather complex) pre-sampling, whilst the general purpose Monte Carlo generators due to a large number of implemented processes tend to use simpler (albeit more generic) phase space sampling algorithms. In addition, the matrix element expressions for these processes are often quite lengthy and thus require complicated calculations. Only recently, with the appearance of modern techniques for automatic computations, their availability *on demand* became feasible for the tree-type processes. With the computation power becoming more and more easily available even very complicated formulas can now be calculated within a reasonable time frame.

2 The Monte Carlo Event Generator AcerMC

The physics processes implemented in **AcerMC** library [3–5] represent such a set of cases. They are all being key background processes for the discovery in the channels characterised by the presence of the

[*]Supported in part by the Polish Government grant KBN 1 P03 091 27 (years 2004-2006) and by the EC FP5 Centre of Excellence "COPIRA" under the contract No. IST-2001-37259.

heavy flavour jets and/or multiple isolated leptons. For the Higgs boson searches, the $t\bar{t}H$, ZH, WH with $H \to b\bar{b}$, the $gg \to H$ with $H \to ZZ^* \to 4\ell$, the $b\bar{b}h/H/A$ with $h/H/A \to \tau\tau, \mu\mu$ are the most obvious examples of such channels.

Let us shortly discuss the motivation for these few Standard Model background processes which are implemented in the **AcerMC 2.x** library.

The $t\bar{t}b\bar{b}$ production is a dominant irreducible background for the Standard Model (SM) and Minimal Supersymmetric Standard Model (MSSM) Higgs boson search in the associated production, $t\bar{t}H$, followed by the decay $H \to b\bar{b}$. Proposed analysis [1] requires identifying four b-jets, reconstruction of both top-quarks in the hadronic and leptonic mode and visibility of the peak in the invariant mass distribution of the remaining b-jets. The irreducible $t\bar{t}b\bar{b}$ background contributes about 60-70% of the total background from the $t\bar{t}$ events ($t\bar{t}b\bar{b}$, $t\bar{t}bj$, $t\bar{t}jj$).

The $Wb\bar{b}$ production is recognised as a substantial irreducible background for the Standard Model (SM) and Minimal Supersymmetric Standard Model (MSSM) Higgs boson search in the associated production, WH, followed by the decay $H \to b\bar{b}$.

The $Wt\bar{t}$ production is of interest because it contributes an overwhelming background [7] for the measurement of the Standard Model Higgs self-couplings at LHC in the most promising channel $pp \to HH \to WWWW$.

The $Z/\gamma^*(\to \ell\ell)b\bar{b}$ production has since several years been recognised as one of the most substantial irreducible (or reducible) backgrounds for the several Standard Model (SM) and Minimal Supersymmetric Standard Model (MSSM) Higgs boson decay modes as well as for observability of the SUSY particles. There is a rather wide spectrum of *regions of interest* for this background. In all cases the leptonic Z/γ^* decay is asked for, but events with di-lepton invariant mass around the mass of the Z-boson mass or with the masses above or below the resonance peak could be of interest. The presented process enters an analysis either by the accompanying b-quarks being tagged as b-jets, or by the presence of leptons from the b-quark semi-leptonic decays in these events, in both cases thus contributing to the respective backgrounds.

The $Z/\gamma^*(\to \ell\ell, \nu\nu, b\bar{b})t\bar{t}$ production is an irreducible background to the Higgs search in the invisible decay mode (case of $Z \to \nu\nu$) in the production with association to the top-quark pair [8]. With the $Z/\gamma^*(\to b\bar{b})$ it is also an irreducible resonant background to the Higgs search in the $t\bar{t}H$ production channel but with the Higgs boson decaying to the b-quark pair.

The complete **EW production** of the $gg, q\bar{q} \to (Z/W/\gamma^* \to)b\bar{b}t\bar{t}$ final state is also provided. It can be considered as a benchmark for the previous process, where only the diagrams with resonant $gg, q\bar{q} \to (Z/\gamma^* \to)b\bar{b}t\bar{t}$ are included. It thus allows the verification of the question, whether the EW resonant contribution is sufficient in case of studying the $t\bar{t}b\bar{b}$ background away from the Z-boson peak, like for the $t\bar{t}H$ with Higgs-boson mass of 120 GeV.

The $gg, q\bar{q} \to t\bar{t}t\bar{t}$ production , interesting process per se, is a background to the possible Higgs self-coupling measurement in the $gg \to HH \to WWWW$ decay, [7].

The $gg, q\bar{q} \to (WWbb \to)f\bar{f}f\bar{f}b\bar{b}$ and $gg, q\bar{q} \to (t\bar{t} \to)f\bar{f}bf\bar{f}\bar{b}$ processes give possibility to study spin correlations in the top-quark pair production and decays as well as the effect from the off-shell production. Those are important for the selection optimisation eg. in the $gg \to H \to WW$ channel, see the discussion in [9]. As an example, Fig. 1 illustrates spin correlation effects in the top-pair production and decays, namely asymmetry in the correlations between lepton and antilepton direction in the rest frame of top-quark, for events generated with $2 \to 6$ matrix element. Such correlation is absent if only $2 \to 2$ matrix element is used for events generation, followed by the independent decays of each top-quark.

A set of **control channels**, i.e. the $q\bar{q} \to Z/\gamma^* \to \ell\ell$, $gg, q\bar{q} \to t\bar{t}$, $q\bar{q} \to W \to \ell\nu$ and $gg \to (t\bar{t} \to)WbW\bar{b}$ processes, have been added to **AcerMC** in order to provide a means of consistency and cross-check studies.

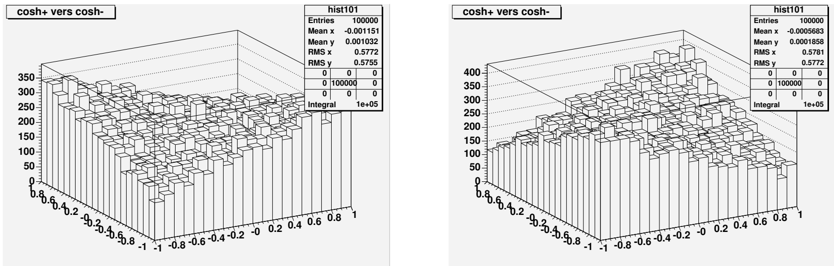

Fig. 1: The correlations between $\cos\Theta$ (azimuthal angle) of lepton and antilepton from $t\bar{t} \to \ell\bar{\nu}b\bar{\ell}\nu\bar{b}$ decays measured in the rest frame of the top-quark with respect to the anti-top quark direction. Left plot is for $gg \to (WWb\bar{b} \to)f\bar{f}f\bar{f}b\bar{b}$ process, right plot for $q\bar{q} \to (WWb\bar{b} \to)f\bar{f}f\bar{f}b\bar{b}$ process.

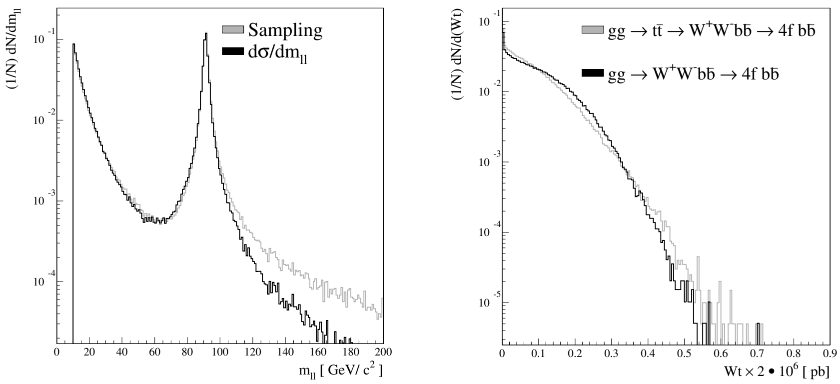

Fig. 2: Left: A representative invariant mass distribution comparisons between the (normalised) sampling functions and the normalised differential cross-section for the $\ell\bar{\ell}$ pair in the process $gg \to Z^0/\gamma^* b\bar{b} \to \ell\bar{\ell}b\bar{b}$ process. Right: The weight distribution of the sampled events for the $gg \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ (light gray histogram) and $gg \to b\bar{b}W^+W^- \to b\bar{b}\ell\bar{\nu}_\ell\bar{\ell}\nu_\ell$ (black histogram) processes. One can observe the well defined weight range for the two processes; as it turns out the weight distribution is even marginally better for the (more complex) second process, possibly because the higher number of sampling channels manage to cover the event topologies in phase space to a better extent.

This completes the list of the native **AcerMC** processes implemented so far. The hard process event, generated with one of these modules, can be completed by the initial and final state radiation, hadronisation and decays, simulated with either `PYTHIA`, `ARIADNE` or `HERWIG` Monte Carlo event generator and (optionally) with `TAUOLA` and `PHOTOS`. Interfaces to all these packages are provided in the distribution releases. The matrix element code has been derived with the help of the `MADGRAPH` package. The phase-space generation is based on the multi-channel self-optimising approach [3] using the modified Kajantie-Byckling formalism for phase space construction and further smoothing of the phase space was obtained by using a modified `ac-VEGAS` algorithm.

The improved and automated phase space handling provided the means to include the $2 \to 6$ processes like e.g. $gg \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\ell\bar{\nu}_\ell q_1\bar{q}_2$ which would with the very complicated phase space topologies prove to be too much work to be handled manually. The studies show that the overall unweighting efficiency which can be reached in the $2 \to 6$ processes by using the recommended phase space structuring is on the order of 10 percent. An example of the implemented sampling functions and the actual differential distributions for the $gg \to Z^0/\gamma^* b\bar{b} \to \ell\bar{\ell}b\bar{b}$ process and of the weight distribution for the $gg \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}\ell\bar{\nu}_\ell q_1\bar{q}_2$ process are shown in Fig.2

In its latest version, the **AcerMC-2.4** package is interfaced also to `ARIADNE 4.1` [12] parton shower model and the LHAPDF structure functions [13].

It is not always the case that the matrix element calculations in the lowest order for a given topology represent the total expected background of a given type. This particularly concerns the heavy flavour content of the event. The heavy flavour in a given event might occur in the hard process of a much simpler topology, as the effect of including higher order QCD corrections (eg. in the shower mechanism). This is the case for the b-quarks present in the inclusive Z-boson or W-boson production, which has a total cross-section orders of magnitude higher than the discussed matrix-element-based $Wb\bar{b}$ or $Zb\bar{b}$ production. Nevertheless, the matrix-element-based calculation is a very good reference point to compare with parton shower approaches in different fragmentation/hadronisation models. It also helps to study matching procedures between calculations in a fixed α_{QCD} order and parton shower approaches. For very exclusive hard topologies matrix-element-based calculations represent a much more conservative approximation than the parton shower ones [6].

3 The AcerDET package

The package **AcerDET** [14] is designed to complete the **AcerMC** generator framework with the easy-to-use simulation and reconstruction algorithms for phenomenological studies on high p_T physics at LHC The package provides, starting from list of particles in the event, the list of reconstructed jets, isolated electrons, muons and photons and reconstructed missing transverse energy. The **AcerDET** represents a simplified version of the package called `ATLFAST` [15], used since several years within ATLAS Collaboration. In the **AcerDET** version some functionalities of the former one have been removed, only the most crucial detector effects are implemented and the parametrisations are largely simplified. Therefore it is not representing in details neither ATLAS nor CMS detectors. Nevertheless, we believe that the package can be well adequate for some feasibility studies of the high p_T physics at LHC.

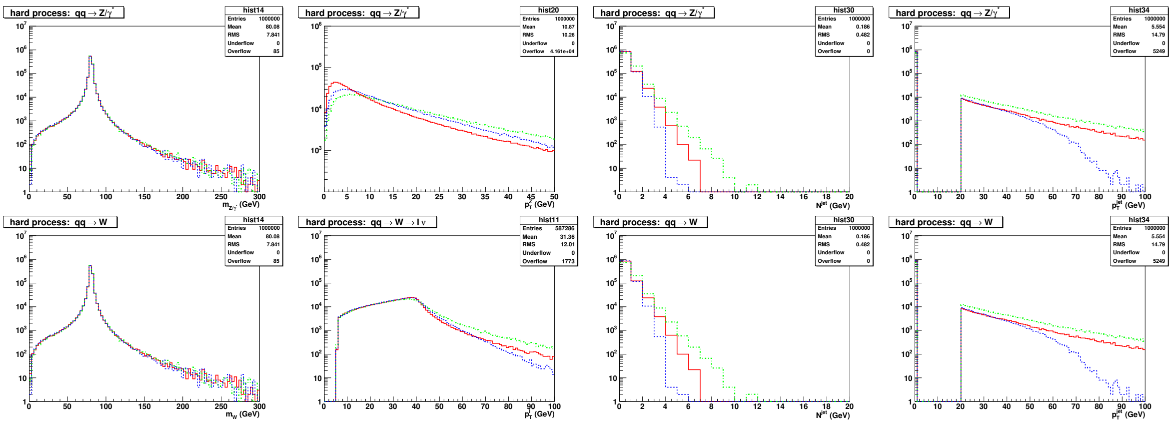

Fig. 3: A few examples of theoretical systematic uncertainties from parton shower model on experimentally observable distributions from Drell-Yan W and Z boson production at LHC (see text).

Fig. 3 shows possible application of the **AcerMC** control processes and **AcerDET** package for studying theoretical systematic uncertainties on the experimentally observed distributions from the parton shower model. The control channels $q\bar{q} \to Z/\gamma^* \to \ell\ell$, and $q\bar{q} \to W \to \ell\nu$ were processed with parton shower model as implemented in `PYTHIA` (red), `HERWIG` (blue) and `ARIADNE` (green). The comparison includes the distributions of the invariant mass of the di-lepton or lepton-neutrino system, transverse momenta of the Z boson, transverse mass of the W, multiplicity of jets from ISR parton shower and transverse momenta of the hardest jets reconstructed with **AcerDET** package. Perfect agreement on the most left plots confirms consistent starting point for the evolution of the ISR QCD parton shower. The differences observed on remaining plots should be attributed to the systematic theoretical uncertainties of the parton shower models.

References

[1] ATLAS Collaboration, *ATLAS Detector and Physics Performance TDR*, CERN-LHCC/99-15 (1999).

[2] CMS Collaboration, Technical Proposal, report CERN/LHCC/94-38 (1994).

[3] B. Kersevan and E. Richter-Was, Eur. Phys. J. **C39** (2005) 439.

[4] B. Kersevan and E. Richter-Was, *AcerMC version 2.4 with interfaces to PYTHIA 6.2, HERWIG 6.5 and ARIADNE 4.1*, hep-ph/0405247, available from `http://borut.home.cern.ch/borut/`

[5] B. Kersevan and E. Richter-Was, Comput. Phys. Commun. **149** (2003) 142.

[6] B. Kersevan and E. Richter-Was, *What is the $Wb\bar{b}$ background at LHC?...*, ATLAS Physics Note, ATL-PHYS-2003-018 (2001).

[7] A. Blondel, A. Clark and F. Mazzucato, ATLAS Physics Note, ATL-PHYS-2002-029 (2002).

[8] J. Gunion, Phys. Rev. Lett. **72** (1994) 199.

[9] N. Krauer and D. Zeppenfeld, Phys.Rev. **D65** (2002) 014021.

[10] E. Barberio and Z. Was, Comp. Phys. Commun. **79** (1994) 291.

[11] S. Jadach, J. H. Kuhn, Z. Was, Comput. Phys. Commun. **64** (1990) 275; M. Jezabek, Z. Was, S. Jadach, J. H. Kuhn, Comput. Phys. Commun. **70** (1992) 69; R. Decker, S. Jadach, J. H. Kuhn, Z. Was, Comput. Phys. Commun. **76** (1993) 361.

[12] L. Lönnblad, Computer Phys. Commun. **71** (1992) 15.
Manual for ARIADNE version 4 available with the distributed ARIADNE code

[13] LHAPDF documentation and code available from:
`http://hepforge.cedar.ac.uk/lhapdf/`

[14] E. Richter-Was, *AcerDET: A particlelevel fast simulation and reconstruction package for phenomenological studies on high p(T) physics at LHC*, hep-ph/0207355.

[15] E. Richter-Was, D. Froidevaux and L. Poggioli, ATLAS Internal Note ATL-PHYS-98-131 (1998).